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(54) **ARRAY CAMERAS INCORPORATING INDEPENDENTLY ALIGNED LENS STACKS**

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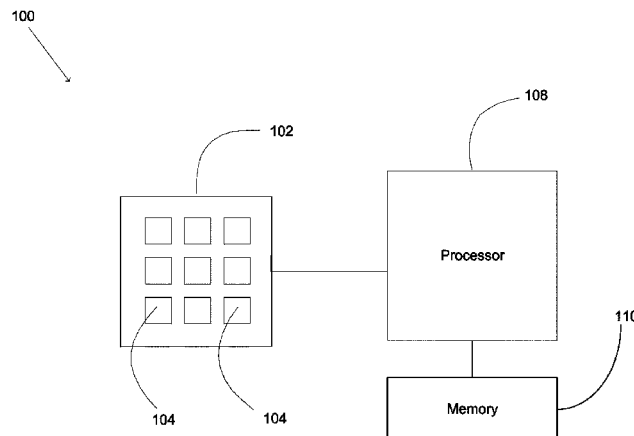(Continued)

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(57) **ABSTRACT**

Array cameras, and array camera modules incorporating independently aligned lens stacks are disclosed. Processes for manufacturing array camera modules including independently aligned lens stacks can include: forming at least one hole in at least one carrier; mounting the at least one carrier relative to at least one sensor so that light passing through the at least one hole in the at least one carrier is incident on a plurality of focal planes formed by arrays of pixels on the at least one sensor; and independently mounting a plurality of lens barrels to the at least one carrier, so that a lens stack in each lens barrel directs light through the at least one hole in the at least one carrier and focuses the light onto one of the plurality of focal planes.

29 Claims, 17 Drawing Sheets

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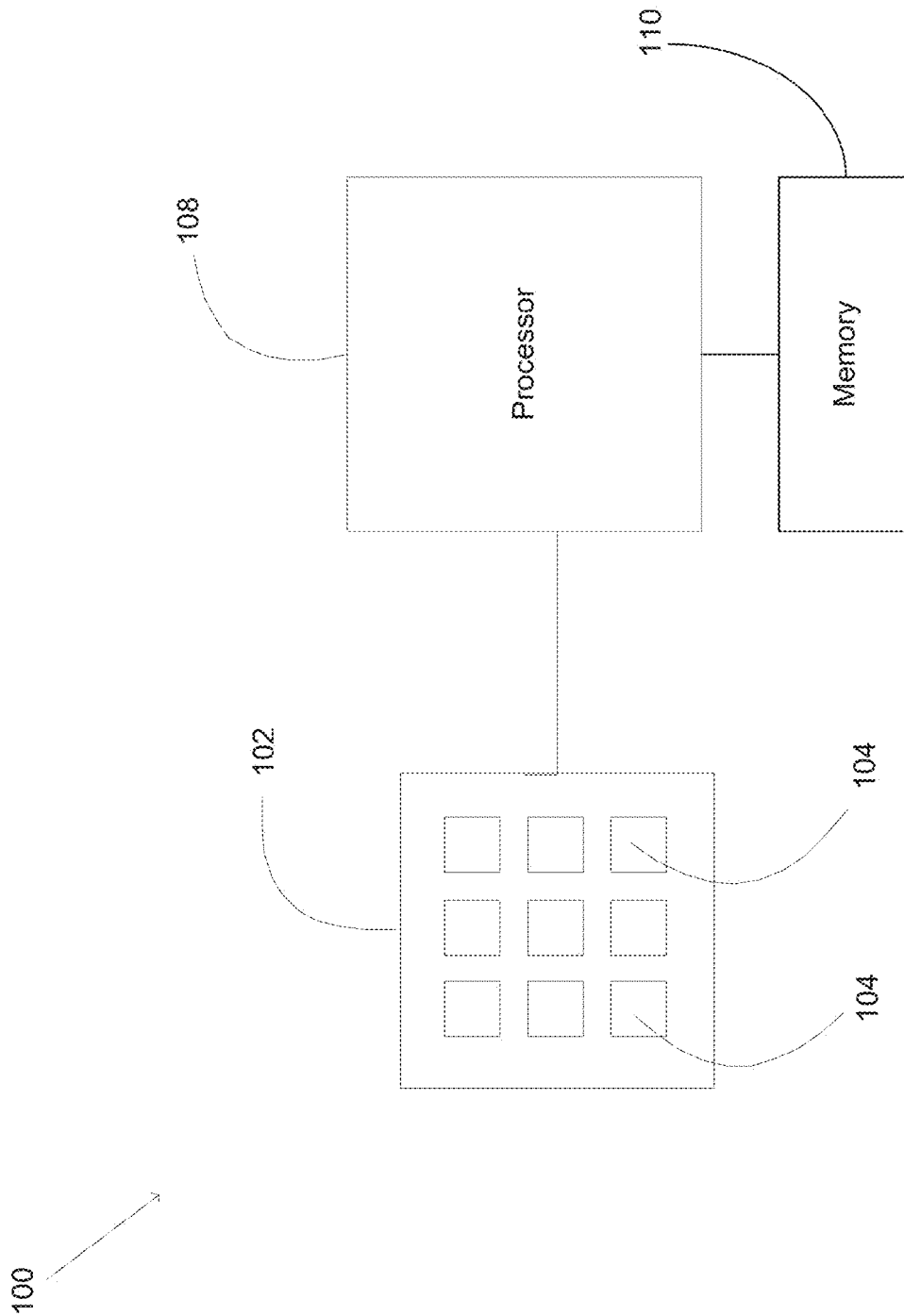
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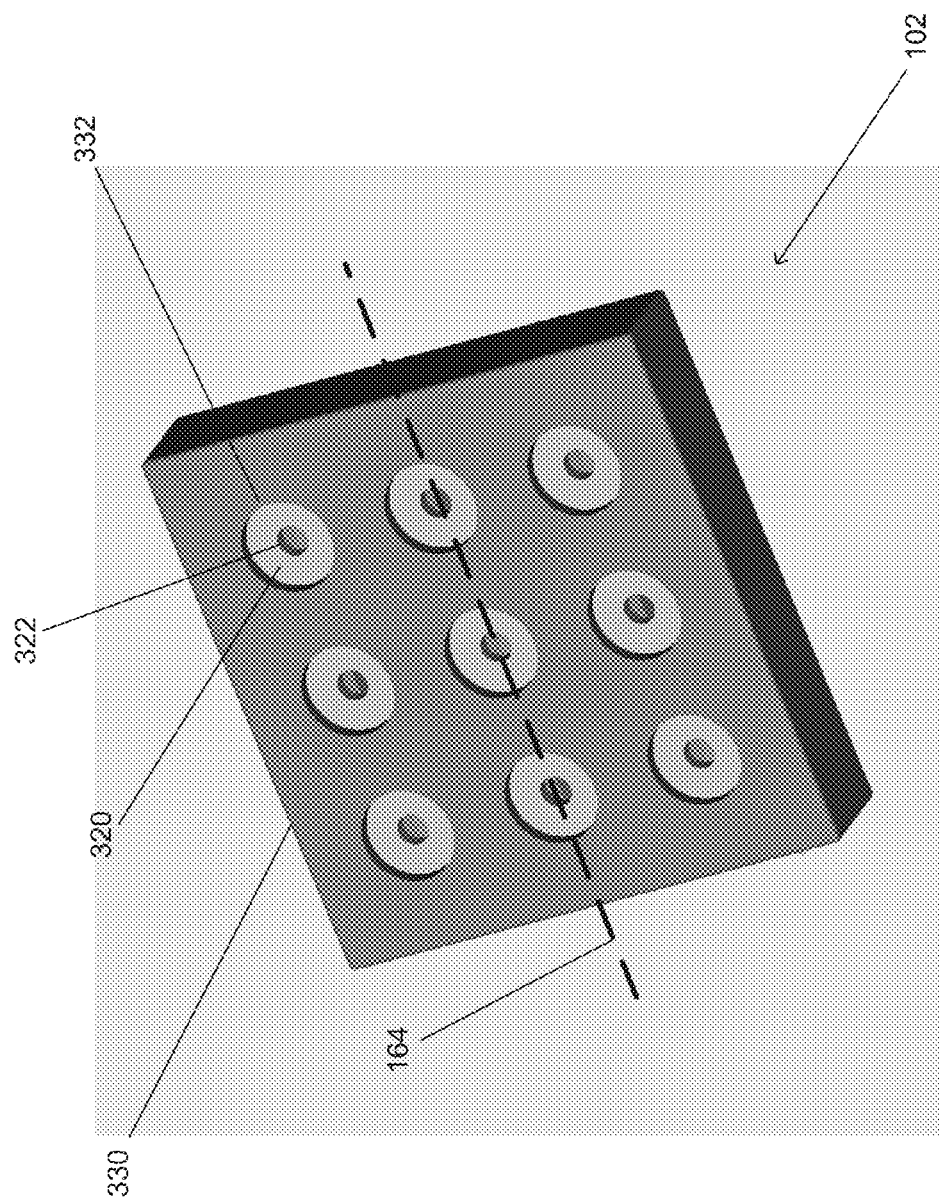
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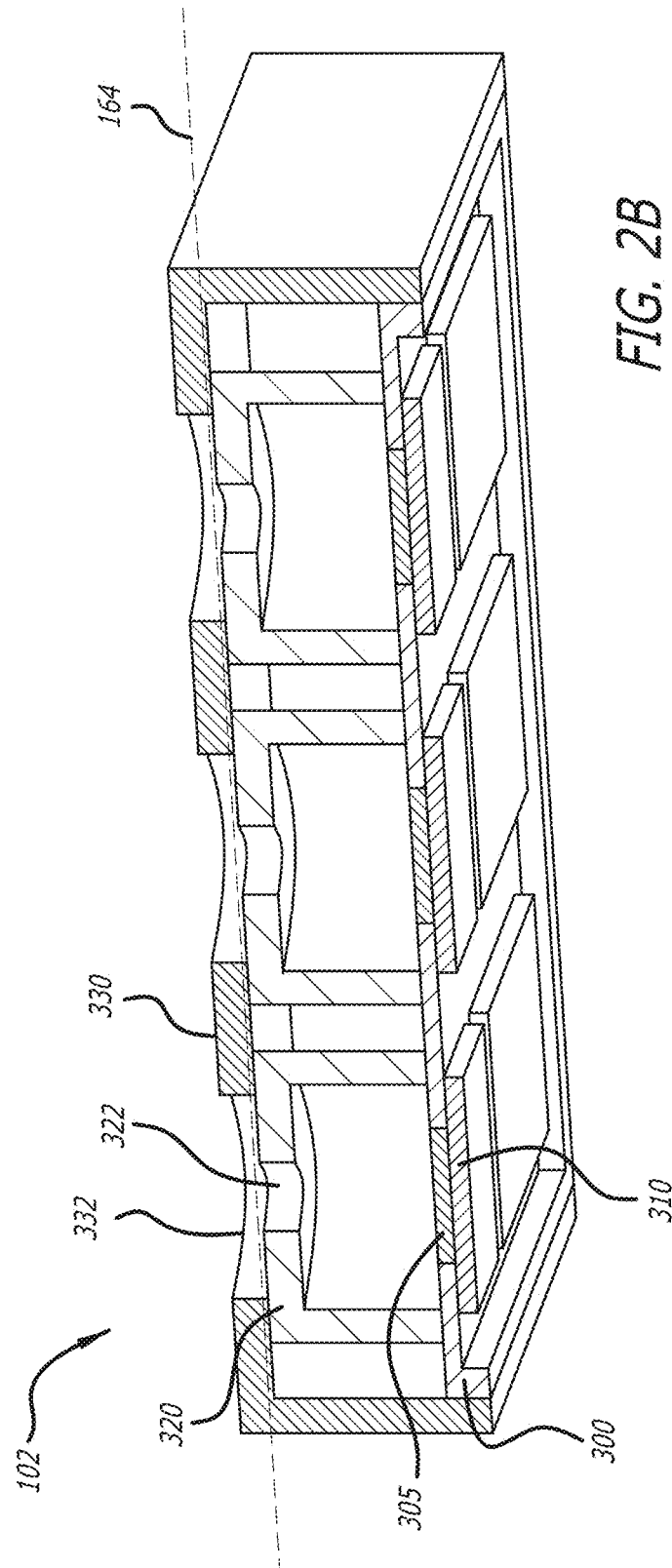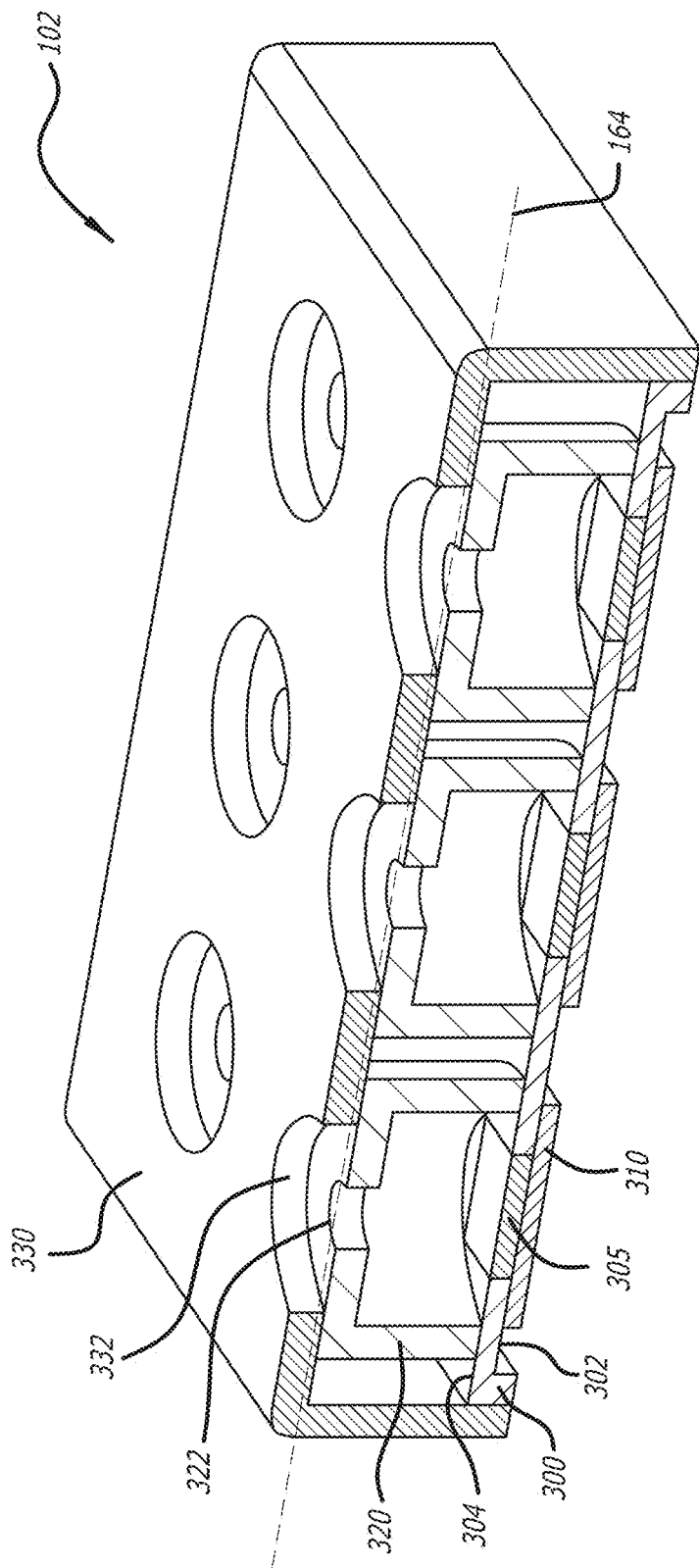
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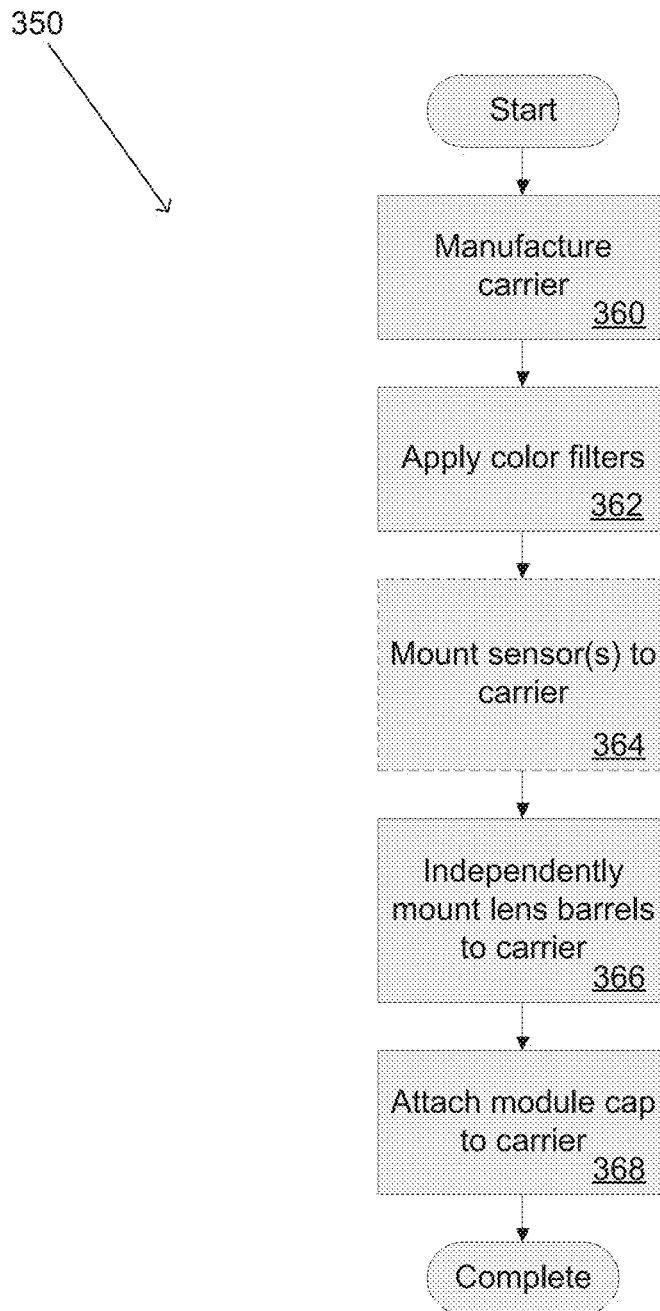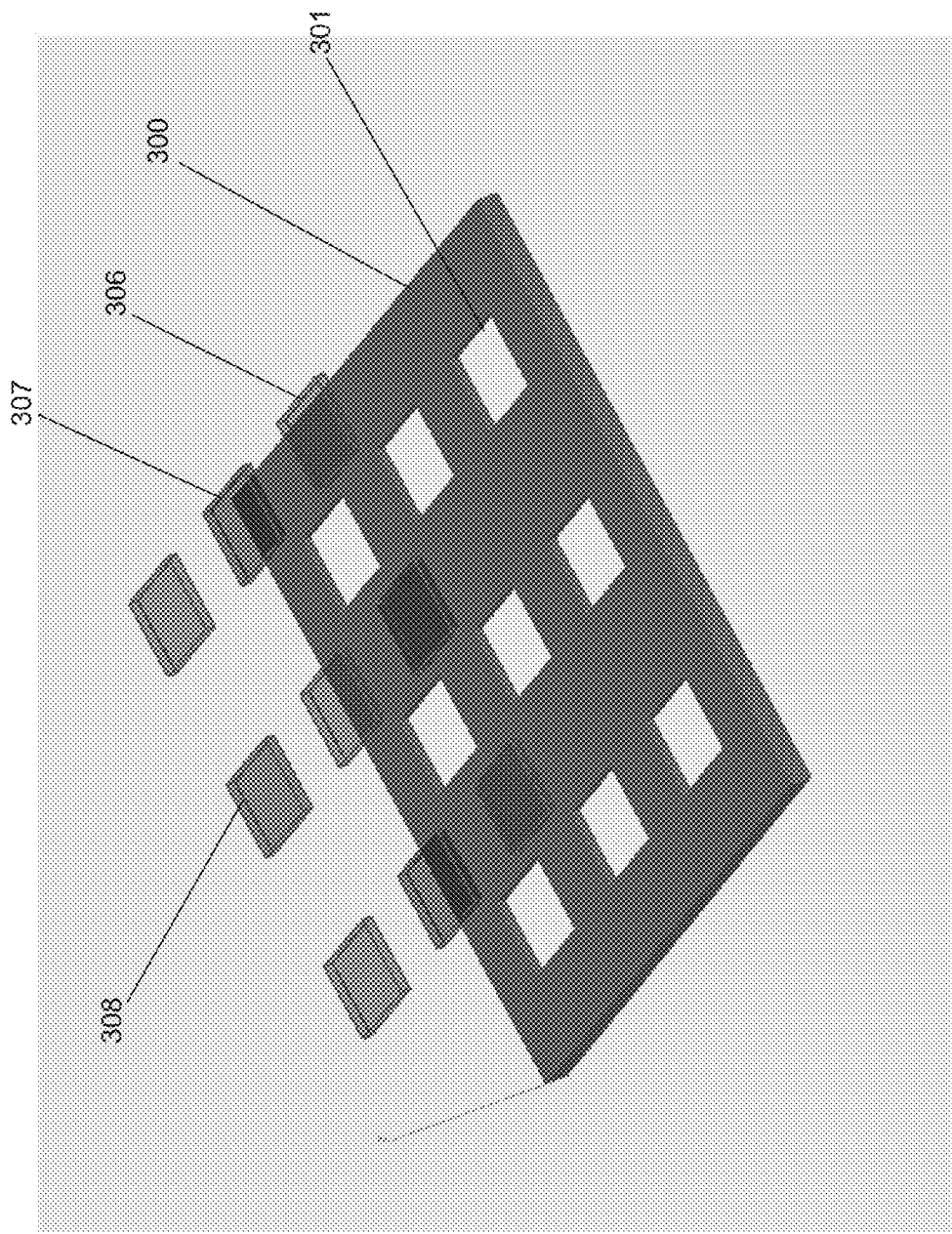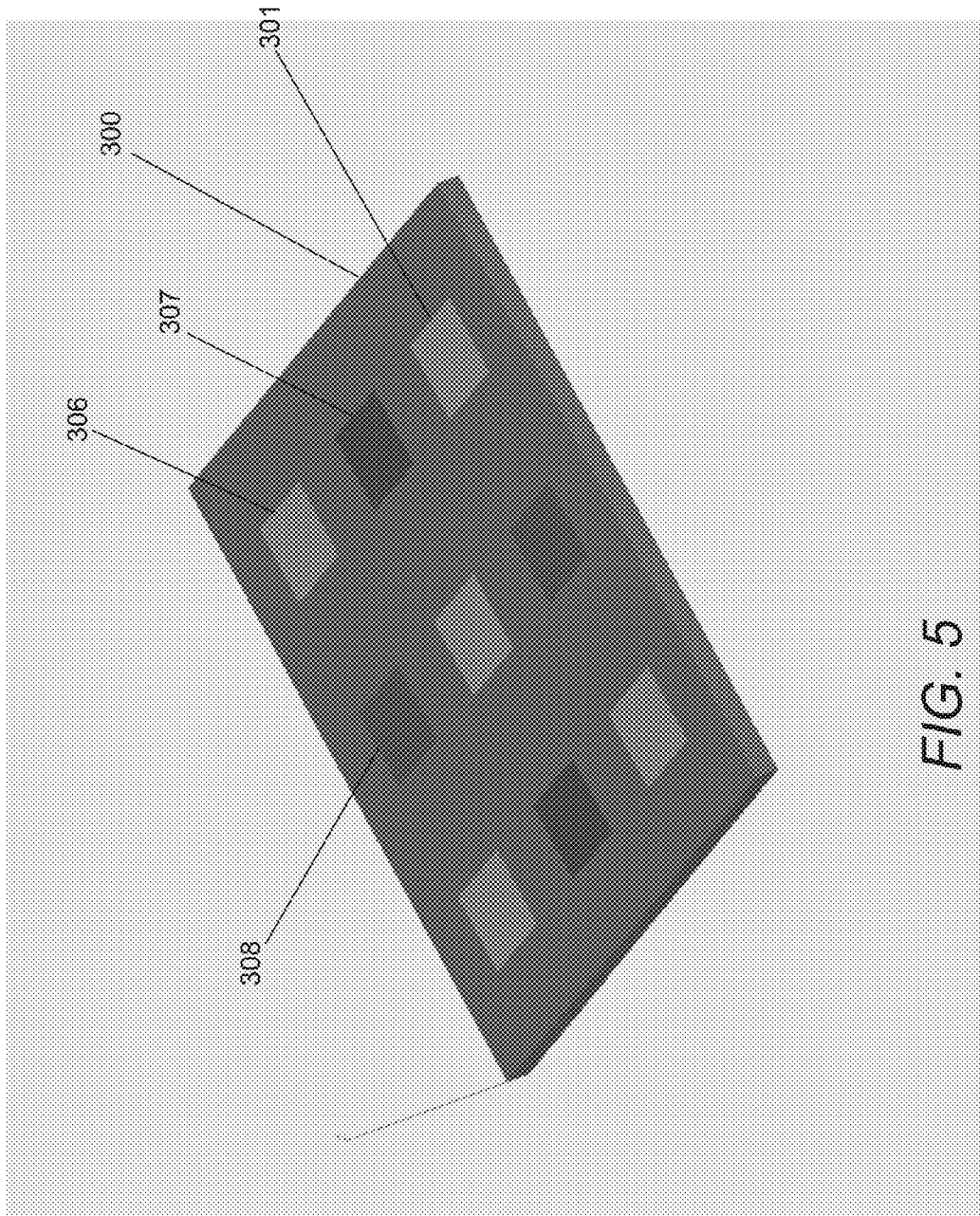
FIG. 2C

350

```
          ┌─────────────┐
          │    Start    │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │ Manufacture │
          │   carrier   │
          │     360     │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │Apply color  │
          │   filters   │
          │     362     │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │Mount sensor(s) to│
          │    carrier  │
          │     364     │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │Independently│
          │mount lens barrels│
          │  to carrier │
          │     366     │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │Attach module cap│
          │  to carrier │
          │     368     │
          └──────┬──────┘
                 │
                 ▼
          ┌─────────────┐
          │  Complete   │
          └─────────────┘
```

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11
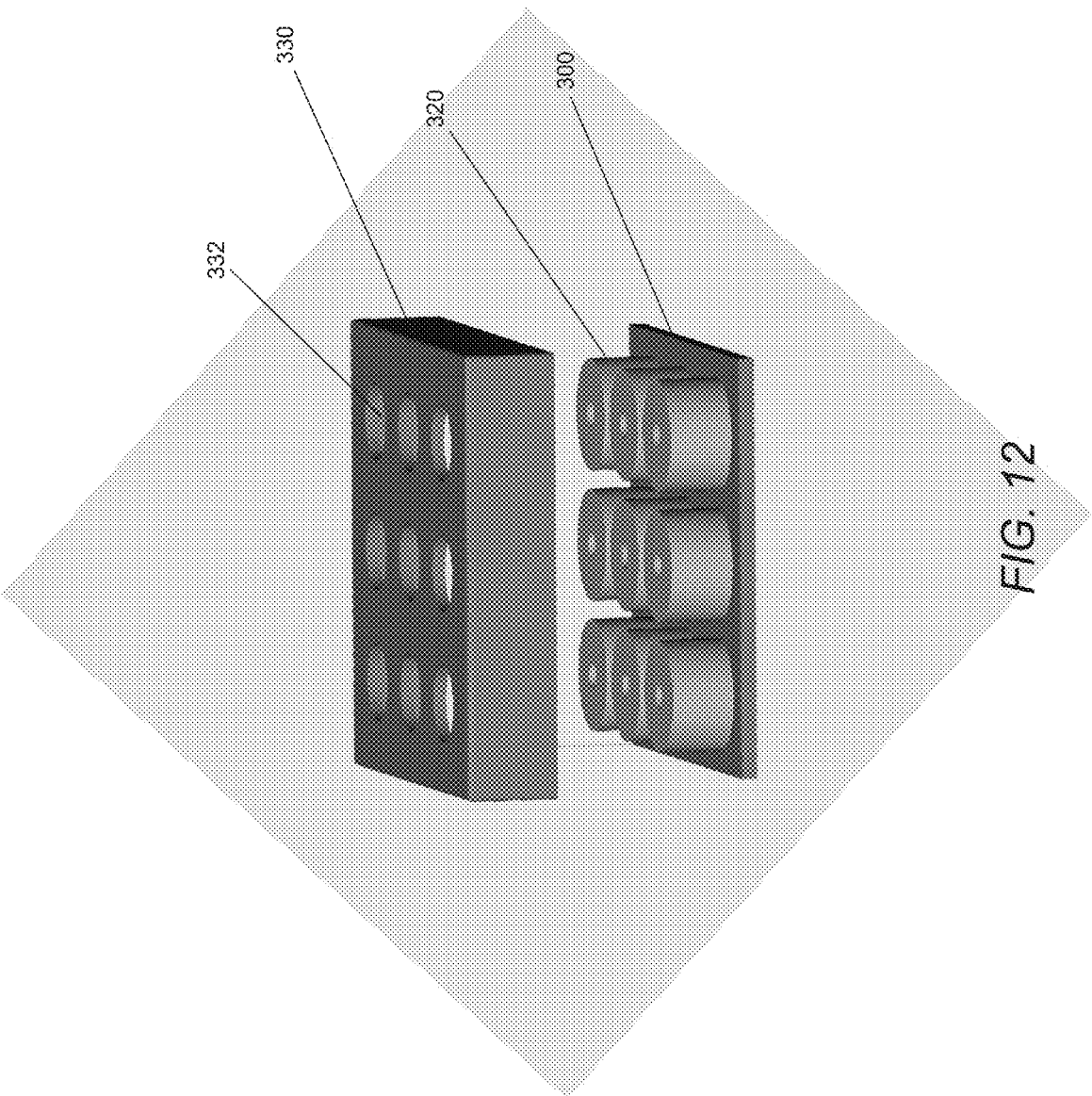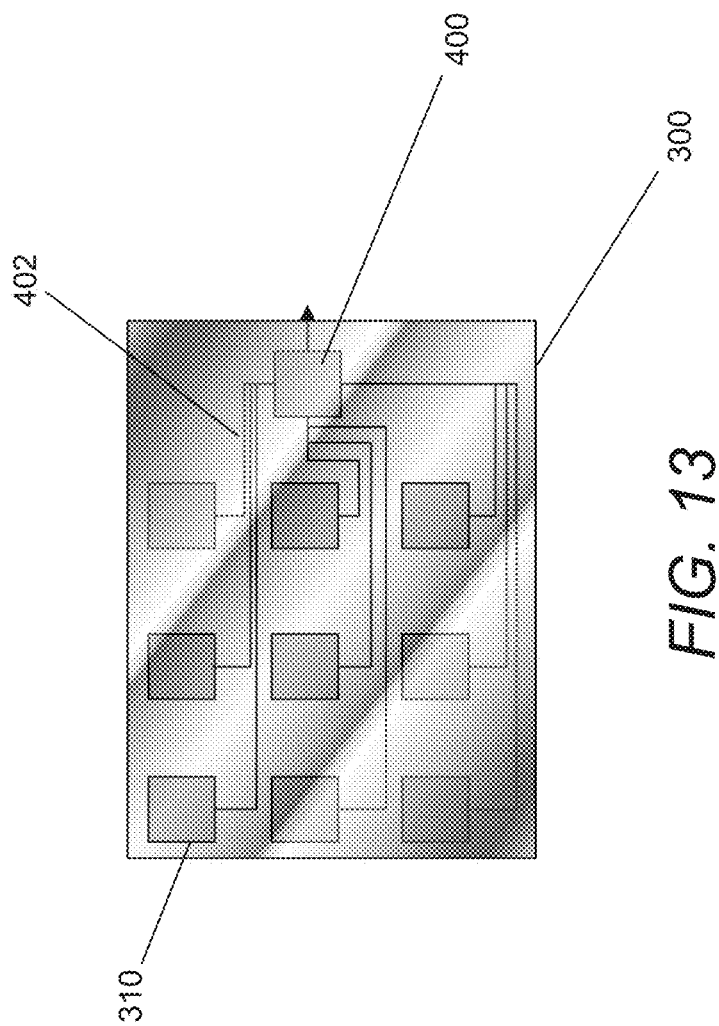
FIG. 12
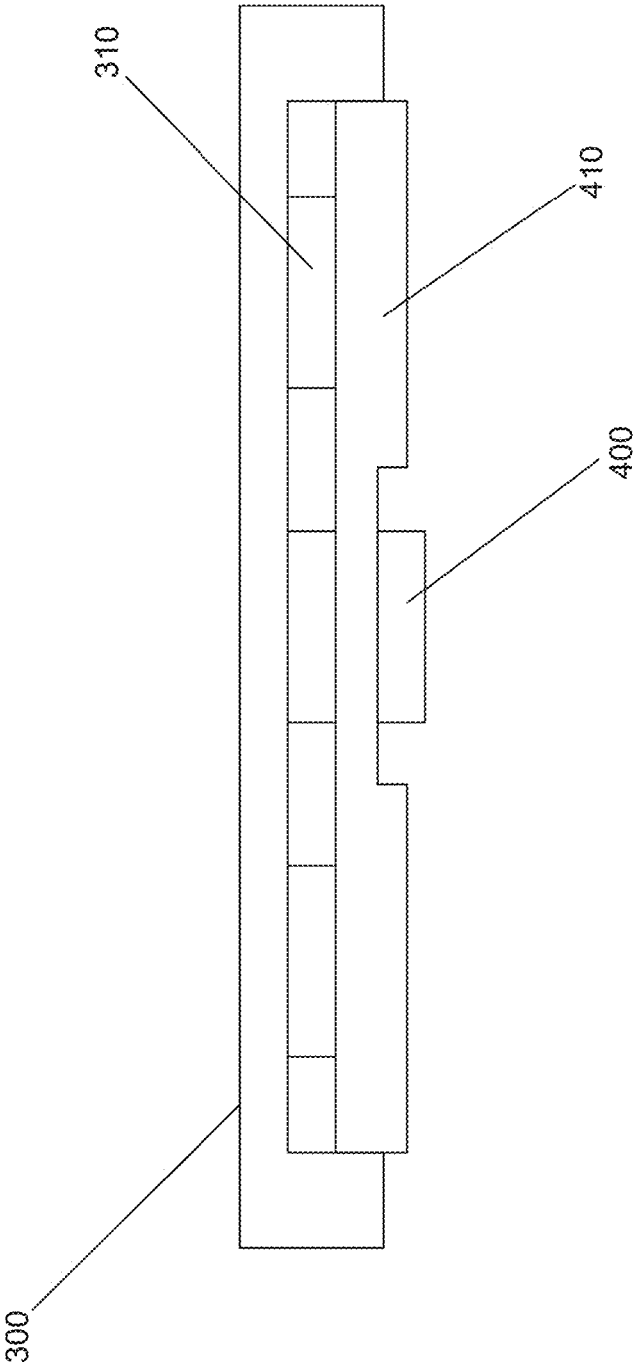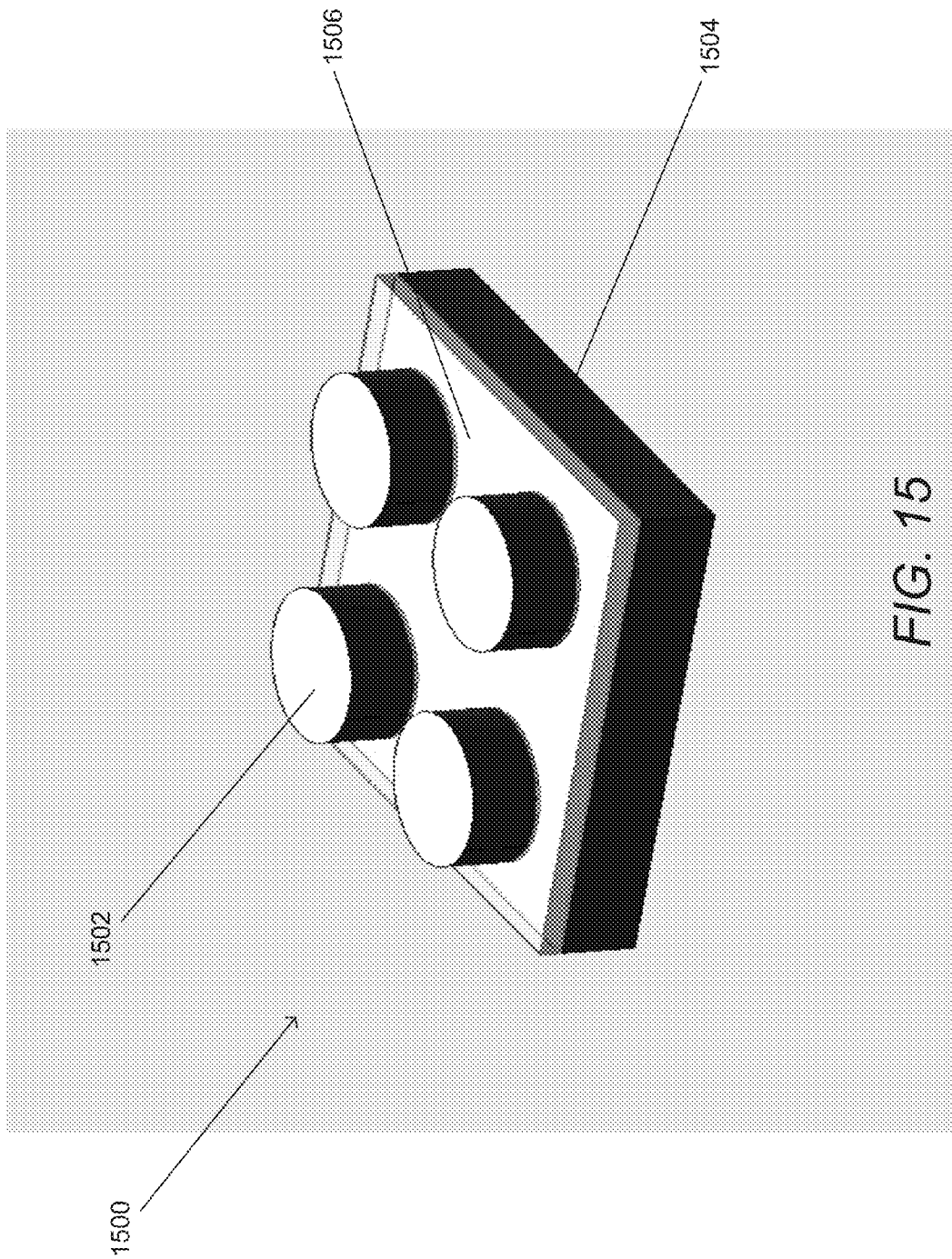
FIG. 13

FIG. 14

1506

1504

1502

1500

FIG. 15
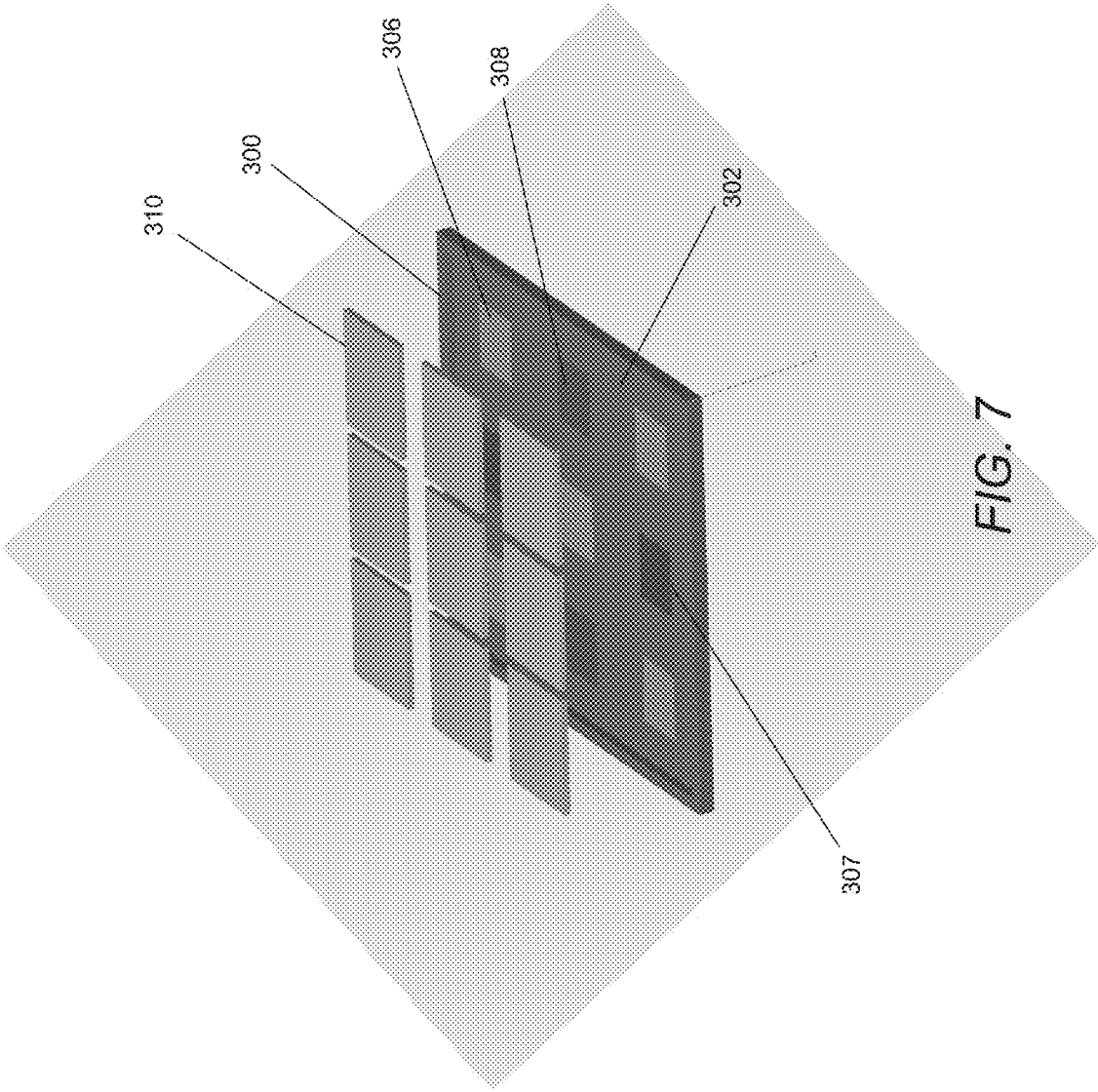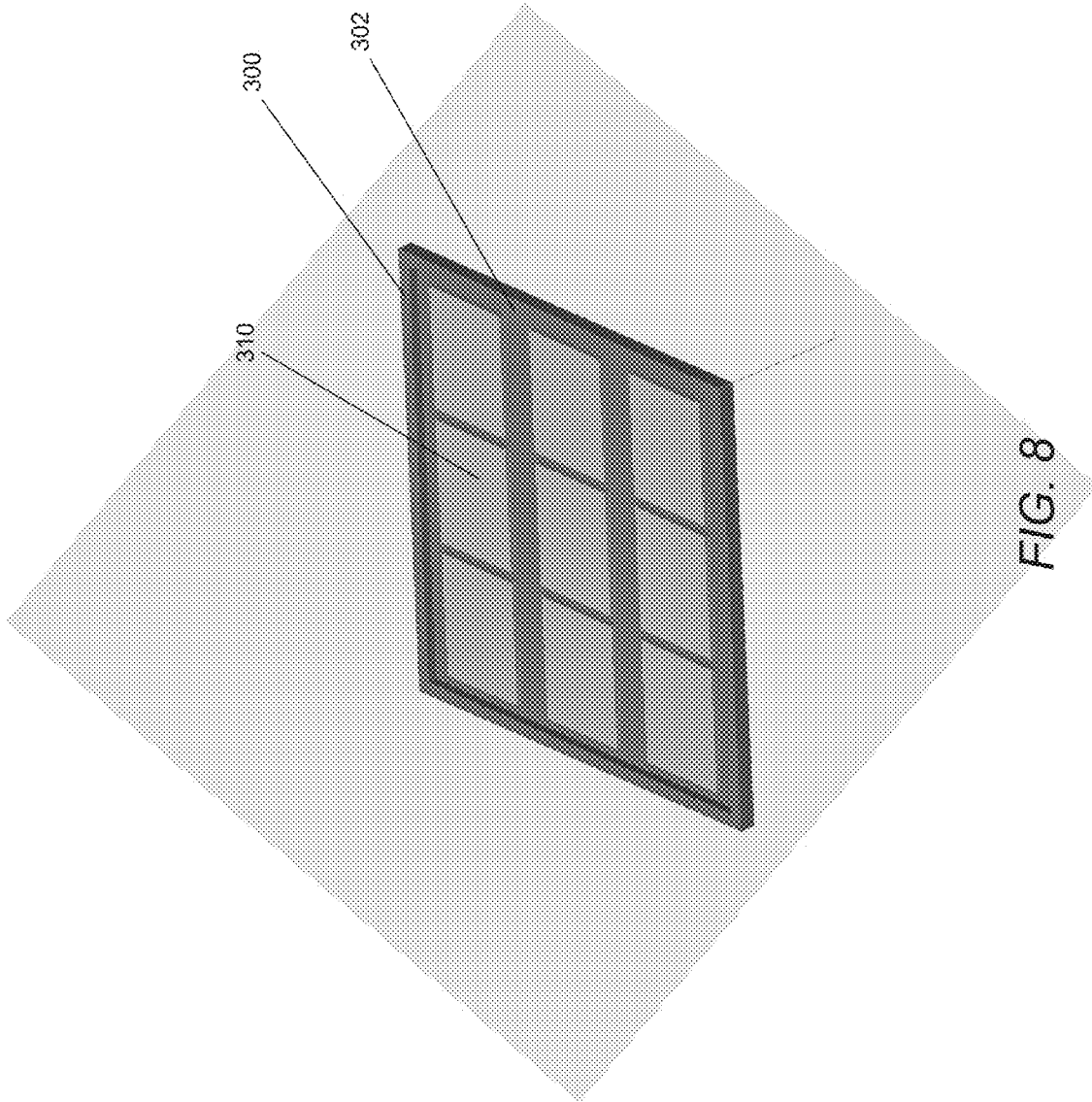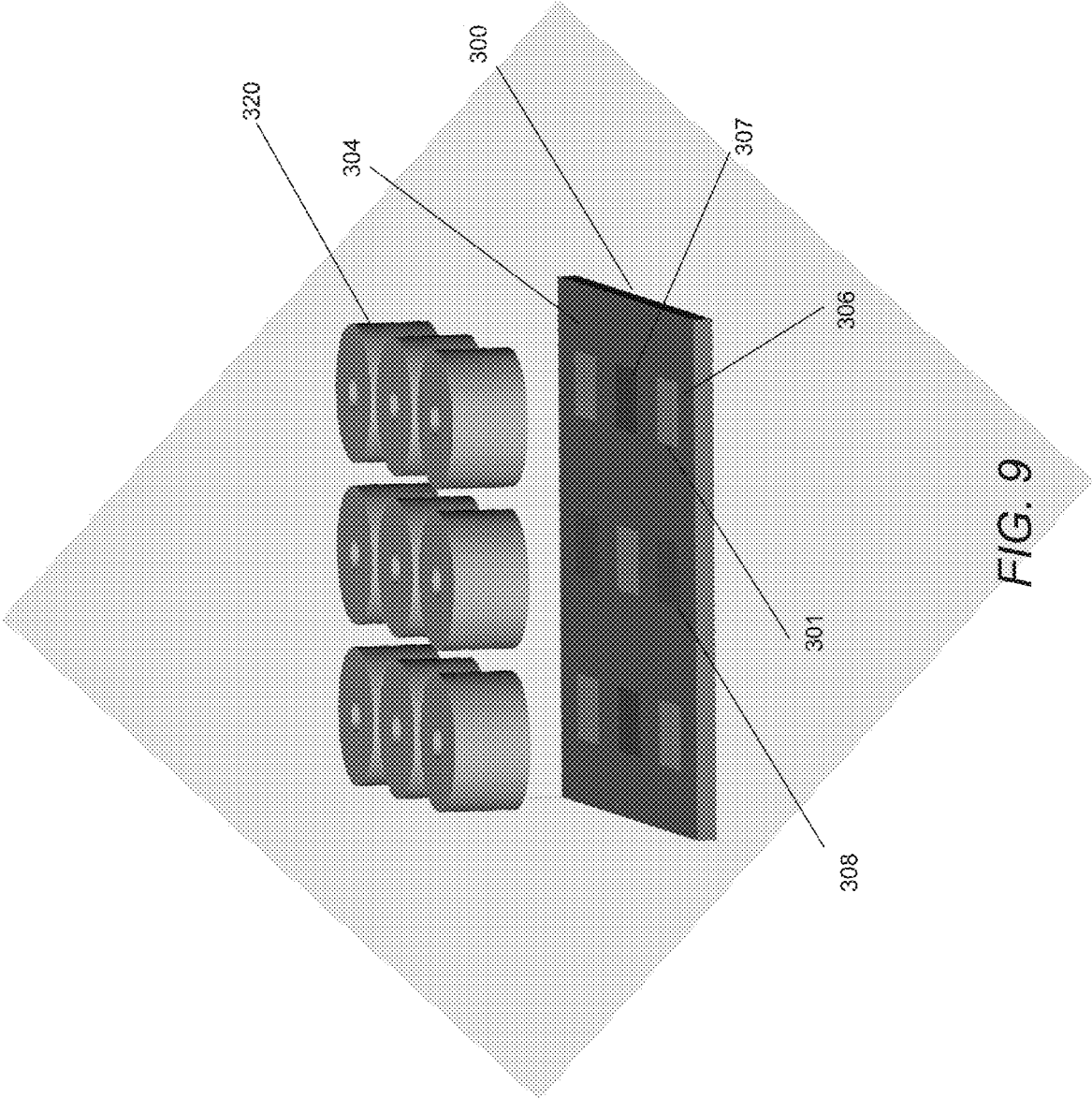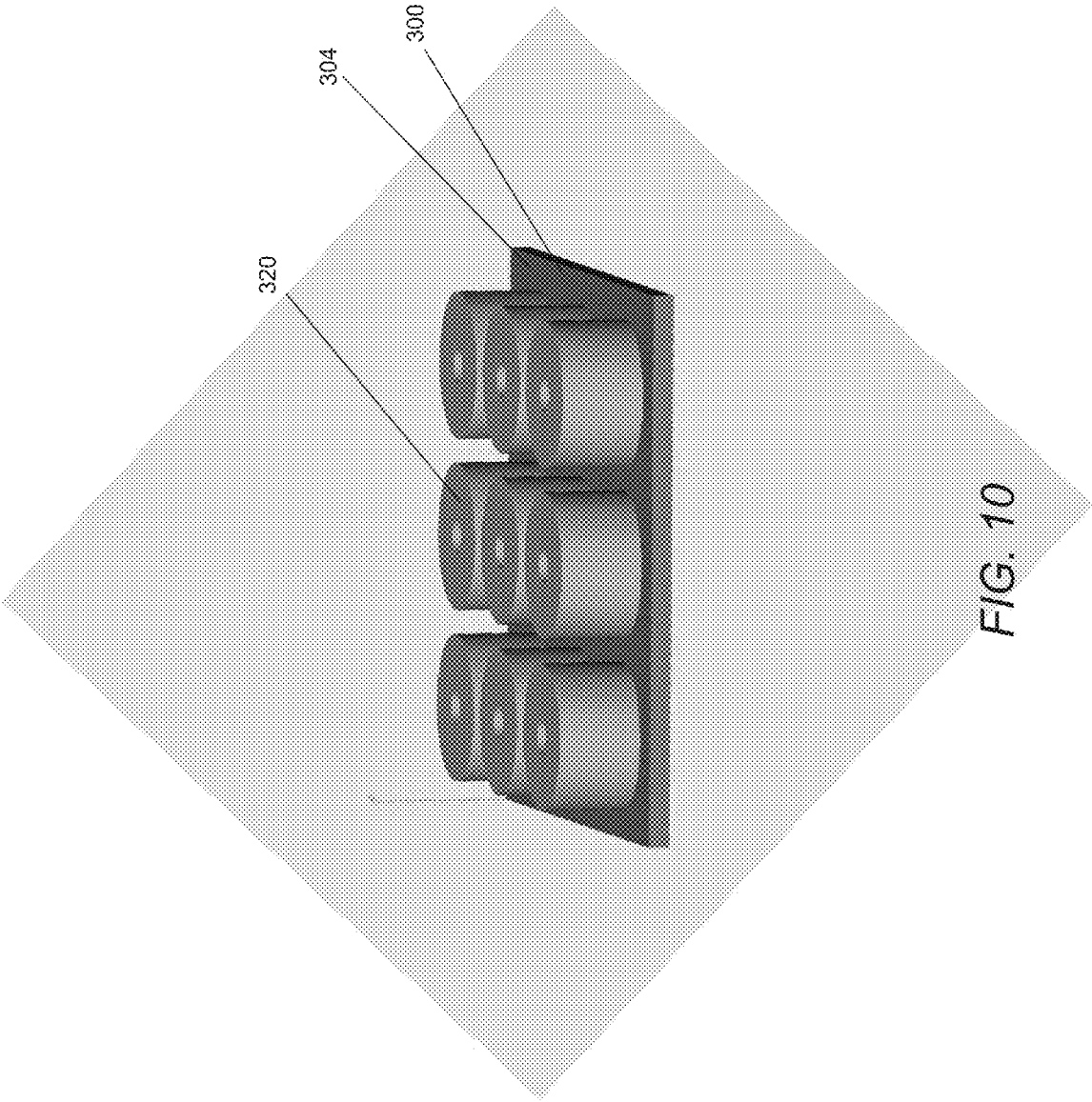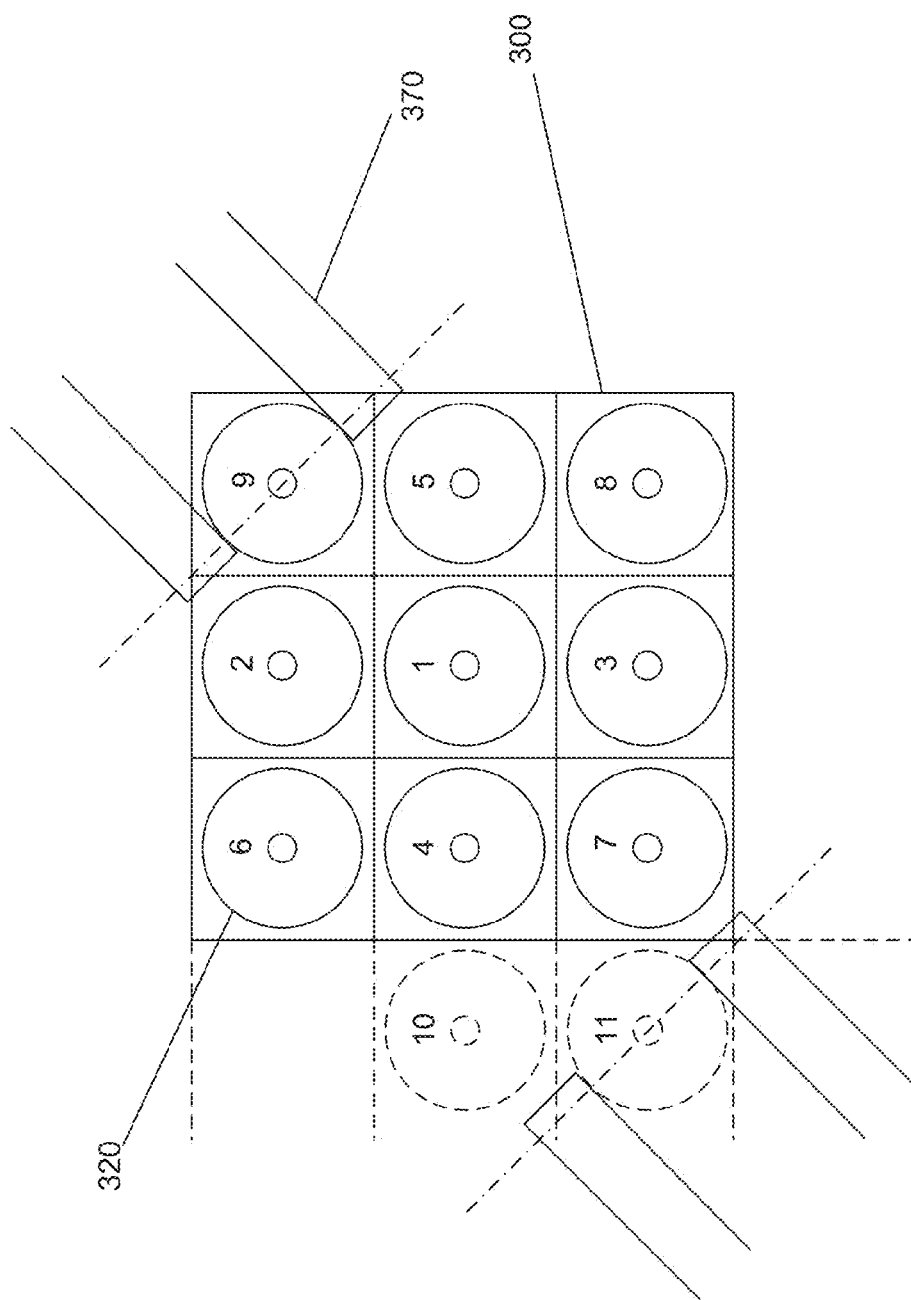
ARRAY CAMERAS INCORPORATING INDEPENDENTLY ALIGNED LENS STACKS

CROSS-REFERENCE TO RELATED APPLICATIONS

The current application is a continuation of U.S. patent application Ser. No. 14/536,537 entitled "Methods of Manufacturing Array Camera Modules Incorporating Independently Aligned Lens Stacks" to Rodda et al., filed Nov. 7, 2014, which application claims priority under 35 U.S.C. §119 (e) to U.S. Provisional Patent Application Ser. No. 61/901, 378 entitled "Non-Monolithic 3–3 Array Module with Discrete Sensors and Discrete Lenses" to Rodda et al., filed Nov. 7, 2013 and U.S. Provisional Patent Application Ser. No. 61/904,947 entitled "Array Camera Modules and Methods of Manufacturing Array Camera Modules Incorporating Independently Aligned Lens Stacks" to Rodda et al., filed Nov. 15, 2013. The disclosures of U.S. Provisional Patent Application Ser. Nos. 61/901,378 and 61/904,947 are hereby incorporated by reference in their entirety.

FIELD OF THE INVENTION

The present application relates generally to array cameras and more specifically to array cameras incorporating independently aligned lens stacks and physically discrete sensors forming an array, a single focal plane sensor utilizing a virtual array, or a monolithic sensor having multiple physical focal planes.

BACKGROUND

Imaging devices, such as cameras, can be used to capture images of portions of the electromagnetic spectrum, such as the visible light spectrum, incident upon an image sensor. For ease of discussion, the term light is generically used to cover radiation across the entire electromagnetic spectrum. In a typical imaging device, light enters through an opening (aperture) at one end of the imaging device and is directed to an image sensor by one or more optical elements such as lenses. The image sensor includes pixels or sensor elements that generate signals upon receiving light via the optical element. Commonly used image sensors include charge-coupled device (CCDs) sensors and complementary metal-oxide semiconductor (CMOS) sensors.

Image sensors are devices capable of converting an optical image into a digital signal. Image sensors utilized in digital cameras are made up of an array of pixels. Each pixel in an image sensor is capable of capturing light and converting the captured light into electrical signals. In order to separate the colors of light and capture a color image, a Bayer filter is often placed over the image sensor, filtering the incoming light into its red, blue, and green (RGB) components which are then captured by the image sensor. The RGB signal captured by the image sensor plus Bayer filter can then be processed and a color image can be created.

Generally, image capture utilizes a single image sensor, to capture individual images, one at a time. A digital camera typically combines both an image sensor and processing capabilities. When the digital camera takes a photograph, the data captured by the image sensor is provided to the processor by the image sensor. Processors are able to control aspects of a captured image by changing image capture parameters of the sensor elements or groups of sensor elements used to capture the image.

SUMMARY OF THE INVENTION

Systems and methods in accordance with embodiments of the invention include processes for constructing array camera modules, array camera modules, and array cameras that include multiple lens stacks separately mounted to a carrier.

One embodiment includes: forming at least one hole in at least one carrier; mounting the at least one carrier relative to at least one sensor so that light passing through the at least one hole in the at least one carrier is incident on a plurality of focal planes formed by arrays of pixels on the at least one sensor; independently mounting a plurality of lens barrels to the at least one carrier, so that a lens stack in each lens barrel directs light through the at least one hole in the at least one carrier and focuses the light onto one of the plurality of focal planes; and mounting a module cap over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels.

In a further embodiment, forming at least one hole in at least one carrier includes forming at least one hole in a single carrier.

In another embodiment, mounting the single carrier relative to at least one sensor includes mounting the single carrier relative to a plurality of sensors.

In a still further embodiment, each of the plurality of sensors is mounted to a first side of the single carrier; each of the plurality of lens barrels is mounted to a second opposite side of the single carrier; and the plurality of sensors comprises a separate sensor for each of the plurality of lens barrels.

In still another embodiment, the at least one hole in the single carrier are spaced to enable an active alignment tool to grip the lens barrel during the active alignment process.

In a yet further embodiment, flip chip mounting is utilized to mount the plurality of sensors to the single carrier.

In yet another embodiment, the plurality of sensors is mounted to a substrate and mounting the single carrier relative to the plurality of sensors comprises mounting the single carrier in a fixed location relative to the substrate.

In a further embodiment again, the plurality of sensors is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In another embodiment again, the at least one hole in the single carrier are spaced to enable an active alignment tool to grip the lens barrel during the active alignment process.

In a further additional embodiment, mounting the single carrier relative to at least one sensor includes mounting the single carrier relative to a single sensor.

In another additional embodiment, the single sensor is mounted to a first side of the single carrier; and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In a still yet further embodiment, the at least one hole in the single carrier are spaced to enable an active alignment tool to grip the lens barrel during the active alignment process.

In still yet another embodiment, flip chip mounting is utilized to mount the single sensor to the single carrier.

In a still further embodiment again, the single sensor is mounted to a substrate and mounting the single carrier relative to the single sensor comprises mounting the single carrier in a fixed location relative to the substrate.

In still another embodiment again, the single sensor is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In a still further additional embodiment, the at least one hole in the single carrier are spaced to enable an active alignment tool to grip the lens barrel during the active alignment process.

In still another additional embodiment, forming at least one hole in at least one carrier comprises forming a ledge in at least one hole in the at least one carrier and mounting at least one spectral filter on the ledge.

A yet further embodiment again also includes mounting at least one spectral filter within at least one hole in the at least one carrier.

In yet another embodiment again, the at least one spectral filter is selected from the group consisting of a color filter and an IR-cut filter.

A further additional embodiment again also includes mounting an interface device relative to the at least one carrier.

In another additional embodiment again, the interface device is mounted to the carrier.

In another further embodiment, the at least one sensor and the interface device are mounted to a substrate and mounting the at least one carrier relative to the at least one sensor comprises mounting the at least one carrier in a fixed location relative to the substrate.

In still another further embodiment, independently mounting a plurality of lens barrels to the at least one carrier comprises using active alignment to separately mount each of the lens barrels to one of the at least one carrier.

In yet another further embodiment, the at least one hole in the at least one carrier are spaced to enable an active alignment tool to grip the lens barrel during the active alignment process.

In another further embodiment again, the at least one opening in the module cap are dimensioned so that the module cap is not visible within the field of view of any of the lens stacks and so that light does not reflect from the module cap into the lens stacks.

In another further additional embodiment, the module cap is mounted to the at least one carrier so that a small air gap exists between the module cap and the top of the lens barrels and the method further comprises applying a small bead of adhesive to each of the lens barrels to seal the air gap between the module cap and the lens barrels.

In still another further embodiment again, the carrier is constructed from a material selected from the group consisting of ceramic and glass.

Still another further additional embodiment includes: forming a plurality of holes in carrier; mounting the carrier relative to a plurality of sensors so that light passing through each of the plurality of holes in the carrier is incident on one of a plurality of focal planes formed by the plurality of sensors; mounting at least one spectral filter within at least one of the plurality of holes in the carrier; independently mounting a plurality of lens barrels to the carrier, so that a lens stack in each lens barrel directs light through the at least one hole in the at least one carrier and focuses the light onto a focal plane formed by a corresponding sensor in the plurality of sensors; and mounting a module cap over the lens barrels so that the module cap is attached to the carrier and a small air gap exists between the module cap and the top of the lens barrels, where the module cap includes a plurality of openings that each admits light into one of the plurality lens stacks contained within the plurality of lens barrels; and applying a small bead of adhesive to each of the lens barrels to seal the air gap between the module cap and the lens barrels.

An array camera module in accordance with an embodiment of the invention includes at least one carrier in which at

least one window is formed; at least one sensor mounted relative to the at least one carrier so that light passing through the at least one window in the at least one carrier is incident on a plurality of focal planes formed by at least one array of pixels on the at least one sensor; a plurality of lens barrels mounted to the at least one carrier, so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels.

In a further embodiment, the at least one carrier is a single carrier.

In another embodiment, each of the plurality of sensors is mounted to a first side of the single carrier; each of the plurality of lens barrels is mounted to a second opposite side of the single carrier; and the plurality of sensors comprises a separate sensor for each of the plurality of lens barrels.

In a still further embodiment, the plurality of sensors is mounted to a substrate and the single carrier is mounted in a fixed location relative to the substrate; and the plurality of sensors is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In still another embodiment, the at least one sensor is a single sensor.

In a yet further embodiment, the single sensor is mounted to a first side of the single carrier; and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In yet another embodiment, the single sensor is mounted to a substrate and the single carrier is mounted in a fixed location relative to the substrate; and the single sensor is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

In a further embodiment again, the at least one sensor is mounted to a substrate and each of a plurality of carriers is mounted in a fixed location relative to the substrate; and each of the plurality of lens barrels is mounted to a separate carrier.

In another embodiment again, each lens barrel forms a separate aperture.

In a further additional embodiment, each lens barrel and corresponding focal plane forms a camera; different cameras within the array camera module image different parts of the electromagnetic spectrum; and the lens stacks contained within the lens barrels differ depending upon the portion of the electromagnetic spectrum imaged by the camera to which the lens barrel belongs.

In another additional embodiment, the lens stacks contained within the lens barrels differ with respect to at least one of: the materials used to construct the lens elements within the lens stacks; the shapes of at least one surface of corresponding lens elements in the lens stacks.

In a still further embodiment again, each lens stack in the lens barrels has a field of view that focuses light so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene.

In still another embodiment again, the pixel arrays of the focal planes define spatial resolutions for each pixel array; the lens stacks focus light onto the focal planes so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene with sub-pixel offsets that provide sampling diversity; and the lens stacks have modulation transfer functions that enable contrast to be resolved at a

spatial frequency corresponding to a higher resolution than the spatial resolutions of the pixel arrays.

In a yet further embodiment again, at least one window in the at least one carrier includes a spectral filter.

In yet another embodiment again, at least one window in at least one carrier comprises a ledge on which the at least one spectral filter is mounted.

In a still further additional embodiment, the at least one spectral filter is selected from the group consisting of a color filter and an IR-cut filter.

In still another additional embodiment, at least one spectral filter is applied to an array of pixels forming a focal plane on at least one of the sensors.

In a yet further additional embodiment, at least one lens stack includes at least one spectral filter.

In yet another additional embodiment, the plurality of lens barrels and the plurality of focal planes form an M×N array of cameras.

In a still further additional embodiment again, the plurality of lens barrels and the plurality of focal planes form a 3×3 array of cameras.

In still another additional embodiment again, the M×N array of cameras comprises a 3×3 group of cameras including: a central reference camera; four cameras that capture image data in a first color channel located in the four corners of the 3×3 group of cameras; a pair of cameras that capture image data in a second color channel located on either side of the central reference camera; and a pair of cameras that capture image data in a third color channel located on either side of the central reference camera.

In another further embodiment, the reference camera is selected from the group consisting of: a camera including a Bayer filter; and a camera that captures image data in the first color channel.

Still another further embodiment also includes an interface device in communication with the at least one sensor, where the interface device multiplexes data received from the at least one sensor and provides an interface via which multiplexed data is read and the imaging parameters of the focal planes formed by the at least one pixel array on the at least one sensor are controlled.

In yet another further embodiment, the interface device is mounted to the carrier and the carrier includes circuit traces that carry signals between the interface device and the at least one sensor; and a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

In another further embodiment again, the at least one sensor and the interface device are mounted to a substrate, which includes circuit traces that carry signals between the interface device and the at least one sensor; the at least one carrier is mounted in a fixed location relative to the at least one sensor; and a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

In another further additional embodiment, the module cap is mounted to the at least one carrier so that a small air gap exists between the module cap and the top of the lens barrels and a small bead of adhesive seals the air gaps between the module cap and the lens barrels.

In still yet another further embodiment, the carrier is constructed from a material selected from the group consisting of ceramic and glass.

Still another further embodiment again includes: a carrier in which a plurality of windows are formed; a plurality of sensors each including an array of pixels, where the plurality

of sensors are mounted relative to the carrier so that light passing through the plurality of windows is incident on a plurality of focal planes formed by the arrays of pixels; a plurality of lens barrels mounted to the at least one carrier so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels.

An embodiment of an array camera includes: a processor; memory containing an image capture application; an array camera module, comprising: at least one carrier in which at least one window is formed; at least one sensor mounted relative to the at least one carrier so that light passing through the at least one window in the at least one carrier is incident on a plurality of focal planes formed by at least one array of pixels on the at least one sensor; a plurality of lens barrels mounted to the at least one carrier, so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels. In addition, the image capture application directs the processor to: trigger the capture of image data by the array camera module; obtain and store image data captured by the array camera module, where the image data forms a set of images captured from different viewpoints; select a reference viewpoint relative to the viewpoints of the set of images captured from different viewpoints; normalize the set of images to increase the similarity of corresponding pixels within the set of images; determine depth estimates for pixel locations in an image from the reference viewpoint using at least a subset of the set of images, wherein generating a depth estimate for a given pixel location in the image from the reference viewpoint comprises: identifying pixels in the at least a subset of the set of images that correspond to the given pixel location in the image from the reference viewpoint based upon expected disparity at a plurality of depths; comparing the similarity of the corresponding pixels identified at each of the plurality of depths; and selecting the depth from the plurality of depths at which the identified corresponding pixels have the highest degree of similarity as a depth estimate for the given pixel location in the image from the reference viewpoint.

In a further embodiment, each lens barrel forms a separate aperture.

In another embodiment, the lens stacks contained within the lens barrels differ with respect to at least one of: the materials used to construct the lens elements within the lens stacks; the shapes of at least one surface of corresponding lens elements in the lens stacks.

In a still further embodiment, the image capture application further directs the processor to fuse pixels from the set of images using the depth estimates to create a fused image having a resolution that is greater than the resolutions of the images in the set of images by: determining the visibility of the pixels in the set of images from the reference viewpoint by: identifying corresponding pixels in the set of images using the depth estimates; and determining that a pixel in a given image is not visible in the reference viewpoint when the pixel fails a photometric similarity criterion determined based upon a comparison of corresponding pixels; and applying scene dependent geometric shifts to the pixels from the set of images that are visible in an image from the reference viewpoint to shift the pixels into the reference viewpoint,

7   8

where the scene dependent geometric shifts are determined using the current depth estimates; and fusing the shifted pixels from the set of images to create a fused image from the reference viewpoint having a resolution that is greater than the resolutions of the images in the set of images.

In a yet further embodiment, the image capture application further directs the processor to synthesize an image from the reference viewpoint by performing a super-resolution process based upon the fused image from the reference viewpoint, the set of images captured from different viewpoints, the current depth estimates, and visibility information.

In yet another embodiment, the plurality of images comprises image data in multiple color channels; and the image capture application directs the processor to compare the similarity of pixels that are identified as corresponding at each of the plurality of depths by comparing the similarity of the pixels that are identified as corresponding in each of a plurality of color channels at each of the plurality of depths.

In a further embodiment again, the array camera module further comprises an interface device in communication with the at least one sensor, where the interface device multiplexes data received from the sensors and provides an interface via which the processor reads multiplexed data and via which the processor controls the imaging parameters of the focal planes formed by the plurality of pixel arrays.

In another embodiment again, the interface device is mounted to the carrier and the carrier includes circuit traces that carry signals between the interface device and the at least one sensor; and a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

In a further embodiment again, the at least one sensor and the interface device are mounted to a substrate, which includes circuit traces that carry signals between the interface device and the at least one sensor; the at least one carrier is mounted in a fixed location relative to the at least one sensor; and a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

Another further embodiment includes: a processor; memory containing an image capture application; an array camera module, comprising: a carrier in which a plurality of windows are formed; a plurality of sensors each including an array of pixels, where the plurality of sensors are mounted relative to the carrier so that light passing through the plurality of windows is incident on a plurality of focal planes formed by the arrays of pixels; a plurality of lens barrels mounted to the at least one carrier so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels. In addition, the image capture application directs the processor to: trigger the capture of image data by the array camera module; obtain and store image data captured by the array camera module, where the image data forms a set of images captured from different viewpoints; select a reference viewpoint relative to the viewpoints of the set of images captured from different viewpoints; normalize the set of images to increase the similarity of corresponding pixels within the set of images; determine depth estimates for pixel locations in an image from the reference viewpoint using at least a subset of the set of images. Furthermore, generating a depth estimate for a given pixel location in the image from the reference viewpoint

includes: identifying pixels in the at least a subset of the set of images that correspond to the given pixel location in the image from the reference viewpoint based upon expected disparity at a plurality of depths; comparing the similarity of the corresponding pixels identified at each of the plurality of depths; and selecting the depth from the plurality of depths at which the identified corresponding pixels have the highest degree of similarity as a depth estimate for the given pixel location in the image from the reference viewpoint.

In still another further embodiment, the pixel arrays of the focal planes define spatial resolutions for each pixel array; the lens stacks focus light onto the focal planes so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene with sub-pixel offsets that provide sampling diversity; and the lens stacks have modulation transfer functions that enable contrast to be resolved at a spatial frequency corresponding to a higher resolution than the spatial resolutions of the pixel arrays; and the image capture application further directs the processor to fuse pixels from the set of images using the depth estimates to create a fused image having a resolution that is greater than the resolutions of the images in the set of images by: determining the visibility of the pixels in the set of images from the reference viewpoint by: identifying corresponding pixels in the set of images using the depth estimates; and determining that a pixel in a given image is not visible in the reference viewpoint when the pixel fails a photometric similarity criterion determined based upon a comparison of corresponding pixels; and applying scene dependent geometric shifts to the pixels from the set of images that are visible in an image from the reference viewpoint to shift the pixels into the reference viewpoint, where the scene dependent geometric shifts are determined using the current depth estimates; and fusing the shifted pixels from the set of images to create a fused image from the reference viewpoint having a resolution that is greater than the resolutions of the images in the set of images.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 conceptually illustrates an array camera in accordance with an embodiment of the invention.

FIGS. 2A-2C schematically illustrate an array camera module in accordance with an embodiment of the invention.

FIG. 3 is a flow chart illustrating a process for manufacturing an array camera module in accordance with an embodiment of the invention.

FIGS. 4 and 5 conceptually illustrate the mounting of filters to a carrier during the construction of an array camera module in accordance with an embodiment of the invention.

FIG. 6 conceptually illustrates cameras forming a π filter group in which red and blue cameras are located on either side of a central green camera that can serve as a reference camera.

FIGS. 7 and 8 conceptually illustrate the mounting of sensors that each contain a single focal plane on a carrier during the construction of an array camera module in accordance with an embodiment of the invention.

FIGS. 9 and 10 conceptually illustrate the mounting of lens barrels to a carrier during the construction of an array camera module in accordance with an embodiment of the invention.

FIG. 11 conceptually illustrates an active alignment tool gripping a lens barrel at a 45 degree angle relative to a 2×2 array formed by the gripped lens barrel and three adjacent lens barrels during the construction of an array camera module in accordance with an embodiment of the invention.

FIG. 12 conceptually illustrates attachment of a module cap to a carrier during the construction of an array camera module in accordance with an embodiment of the invention.

FIG. **13** conceptually illustrates an array camera module including a carrier on which a 3×3 array of sensors and an interface device are mounted in accordance with an embodiment of the invention.

FIG. **14** conceptually illustrates a substrate assembly that can be utilized in the construction of an array camera module in accordance with an embodiment of the invention.

FIG. **15** conceptually illustrates an array camera module in which a single sensor is attached to a glass carrier in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

Turning now to the drawings, array camera modules incorporating independently aligned lens stacks and methods for constructing array camera modules incorporating independently aligned lens stacks are described. An array camera is an image capture device that includes multiple lens stacks or optical channels that direct light onto a corresponding number of focal planes, enabling the capture of multiple images of a scene using the focal planes. The light received via each of the lens stacks passes through a separate aperture and so each of the captured images constitutes a different view of the scene. In a number of embodiments, super-resolution processes such as those described in U.S. Patent Publication No. 2012/0147205 entitled "Systems and Methods for Synthesizing High Resolution Images Using Super-Resolution Processes", to Lelescu et al., are utilized to synthesize a higher resolution two dimensional (2D) image or a stereo pair of higher resolution 2D images from the lower resolution images in the light field captured by an array camera. The terms high or higher resolution and low or lower resolution are used here in a relative sense and not to indicate the specific resolutions of the images captured by the array camera. The disclosure within U.S. Patent Publication No. 2012/0147205 concerning processes for fusing higher resolution images from a set of images captured from different viewpoints, synthesizing higher resolution images from a set of images captured from different viewpoints using super-resolution processing, synthesizing high resolution images from virtual viewpoints, and for dynamically refocusing synthesized high resolution images is hereby incorporated by reference in its entirety.

The term focal plane can be used to describe a region on a sensor containing an array of pixel elements configured to capture an image based upon light directed onto the focal plane via a lens stack or optical channel. In many embodiments, each focal plane is implemented using a separate sensor. In a number of embodiments, array cameras are implemented using sensors that include multiple focal planes, where each focal plane receives light from a separate optical channel. As such, the sensor is configured to separately and (in many instances) independently capture and output image data from each of the focal planes.

The array cameras disclosed in U.S. Patent Publication No. 2011/0069189 entitled "Capturing and Processing of Images Using Monolithic Camera Array with Heterogeneous Imagers", to Venkataraman et al. include examples of array cameras in which the lens stacks of the array camera are implemented as a single lens stack array that is aligned and mounted to a sensor. However, the large number of tolerances involved in the manufacture of a lens stack array can result in the different optical channels having varying focal lengths. The combination of all the manufacturing process variations typically results in a deviation of the actual ("first order") lens parameters—such as focal

length—from the nominal prescription. As a result, each optical channel can have a different axial optimum image location. Consequently, the lens stack array typically cannot be placed a distance that corresponds with the focal length of each lens stack within an array camera module. Notably, these manufacturing tolerances may result in different focal lengths even as between lens stack arrays fabricated from the same manufacturing process. The disclosure within U.S. Patent Publication No. 2011/0069189 regarding the implementation of different array camera architectures including monolithic array cameras, non-monolithic array cameras, and arrays of array cameras is hereby incorporated by reference herein in its entirety. Array cameras in accordance with embodiments of the invention are constructed by independently aligning each lens stack with respect to a corresponding focal plane. In this way, each lens stack can be optimally aligned with respect to a corresponding focal plane.

In several embodiments, an active alignment process is utilized to align each lens stack with respect to its corresponding focal plane. In the context of the manufacture of camera systems, the term active alignment typically refers to a process for aligning an optical system (e.g. a lens stack array) with an imaging system (e.g. comprising a monolithic sensor) to achieve a final desirable spatial arrangement by evaluating the efficacy of the configuration as a function of the spatial relationship between the optical system and the imaging system. Typically, this process is implemented by using the configuration to capture and record image data (typically of a known target) in real time as the optical system is moving relative to the imaging system. As the optical system is moved relative to the imaging system, the spatial relationship between the two changes, and the characteristics of the recorded image data also change correspondingly. This recorded image data may then be used to align the optical system relative to the imaging system in a desired manner. For example, active alignment can generally be used to determine a spatial relationship that results in a camera that is capable of recording images that exceed a threshold image quality.

In several embodiments, an array camera module is constructed using a ceramic carrier in which windows through the ceramic carrier are formed. A single sensor or multiple sensors can be fixed to one side of the ceramic carrier to form the focal planes of the array camera module and lens barrels containing lens stacks can be affixed to the other side of the ceramic carrier so that the lens stacks direct light onto the focal planes of the one or more sensors through the openings in the ceramic carrier. The ceramic carrier is rigid and can have a co-efficient of thermal expansion (CTE) selected to match the CTE of the sensor. In this way, the ceramic carrier reduces the likelihood that mismatches in thermal expansion will result in changes in the alignment between the lens stacks and corresponding focal planes that deteriorate the quality of the images that can be synthesized using the image data captured by the focal planes. In other embodiments, any of a variety of substrate materials exhibiting rigidity and low CTE can be utilized as a substitute for a ceramic carrier including (but not limited to) a transparent glass substrate. Furthermore, a variety of mounting techniques can be utilized including (but not limited to) mounting one or more sensors to a substrate and mounting the lens barrels containing the lens stacks to a carrier, or mounting individual camera modules to a substrate. Array cameras constructed using array camera modules incorporating independently aligned lens stacks and methods for constructing array camera modules incorporating independently aligned lens stacks are discussed further below.

Array Cameras Including Modules Incorporating Independently Aligned Lens Stacks

An array camera including an array camera module in accordance with an embodiment of the invention is illustrated in FIG. 1. The array camera 100 includes an array camera module 102 including an array of cameras 104. The array camera module 102 is configured to communicate with a processor 108, which can execute an image capture application stored as non-transitory machine readable instructions within a memory 110. The memory 110 can also be utilized to store image data captured by the array camera module.

The array camera module 102 includes an array of focal planes on which images are formed by an array of lens stacks. Each lens stack creates an optical channel that forms an image of the scene on an array of light sensitive pixels within a corresponding focal plane. Each lens stack is independently mounted within array camera module 102 to form a single camera 104 with the corresponding focal plane on which the lens stack forms an image. In many embodiments, each lens stack can be actively aligned with respect to its corresponding focal plane to improve the quality of the image data capture by the focal plane.

The pixels within a focal plane of a camera 104 generate image data that can be sent from the array of cameras 104 to the processor 108. In many embodiments, the lens stack within each optical channel have fields of view that focus light so that pixels of each focal plane sample the same object space or region within the scene. In several embodiments, the lens stacks are configured so that the pixels that sample the same object space do so with sub-pixel offsets to provide sampling diversity that can be utilized to recover increased resolution through the use of super-resolution processes. The term sampling diversity refers to the fact that the images from different viewpoints sample the same object in the scene but with slight sub-pixel offsets. By processing the images with sub-pixel precision, additional information encoded due to the sub-pixel offsets can be recovered when compared to simply sampling the object space with a single image. In order to enable the recovery of higher resolution information, the lens stacks are designed to have a Modulation Transfer Function (MTF) that enables contrast to be resolved at a spatial frequency corresponding to the higher resolution and not at the spatial resolution of the pixels that form a focal plane.

In the illustrated embodiment, the cameras 104 are configured in a 3×3 array. In other embodiments, any of a variety of M×N camera array configurations can be utilized including linear arrays (i.e. 1×N arrays). Each camera 104 in the array camera module 102 is capable of capturing an image of the scene. The sensor elements utilized in the focal planes of the cameras 104 can be individual light sensing elements such as, but not limited to, traditional CIS (CMOS Image Sensor) pixels, CCD (charge-coupled device) pixels, high dynamic range sensor elements, multispectral sensor elements and/or any other structure configured to generate an electrical signal indicative of light incident on the structure. In many embodiments, the sensor elements of each focal plane have similar physical properties and receive light via the same optical channel and color filter (where present). In several embodiments, the sensor elements have different characteristics and, in many instances, the characteristics of the sensor elements are related to the color filter applied to each sensor element.

In a variety of embodiments, color filters in individual cameras can be used to pattern the camera module with π filter groups as further discussed in U.S. Patent Publication No. 2013/0293760 entitled "Camera Modules Patterned with pi Filter Groups", the disclosure from which related to filter patterns that can be utilized in the implementation of an array camera is incorporated by reference herein in its entirety. Any of a variety of color filter configurations can be utilized where cameras in each color channel are distributed on either side of the center of the camera. The cameras can be used to capture data with respect to different colors, or a specific portion of the spectrum. In a number of embodiments, cameras image in the near-IR, IR, and/or far-IR spectral bands. In contrast to applying color filters to the pixels of the camera, color filters in many embodiments of the invention are mounted to a ceramic carrier to which one or more sensors and/or the lens stacks are mounted, or included in the lens stack. Where the sensor(s) and lens stacks are mounted to a glass substrate, the color filters can be applied to the glass substrate. For example, a green color camera can include a lens stack with a green light filter that allows green light to pass through the optical channel. In many embodiments, the pixels in each focal plane are the same and the light information captured by the pixels is differentiated by the color filters in the corresponding lens stack for each filter plane. The inclusion of spectral filters within array camera modules in accordance with various embodiments of the invention can be implemented in a variety of other ways including (but not limited to) by applying color filters to the pixels of the focal planes of the cameras similar to the manner in which color filters are applied to the pixels of a conventional color camera. In several embodiments, at least one of the cameras in the camera module can include uniform color filters applied to the pixels in its focal plane. In many embodiments, a Bayer filter pattern is applied to the pixels of at least one of the cameras in a camera module. In a number of embodiments, camera modules are constructed in which color filters are utilized in both the lens stacks and on the pixels of the imager array.

In several embodiments, the processor 108 is configured to take the image data captured by the sensor and synthesize high resolution images. In a number of embodiments, the processor 108 is configured to measure distances to or depth of objects in the scene using the set of images captured by the array camera module. In many embodiments, the process of synthesizing high resolution images from a set of images captured by the array camera module also involves generating depth information with respect to objects visible within the field of view of the array camera. U.S. Pat. No. 8,619,082 entitled "Systems and Methods for Parallax Detection and Correction in Images Captured Using Array Cameras that Contain Occlusions using Subsets of Images to Perform Depth Estimation" to Ciurea et al. discloses techniques for estimating depth using sets of images captured from different viewpoints. The disclosure within U.S. Pat. No. 8,619,082 concerning estimating depth and generating a depth map using multiple images of a scene and synthesizing images from different perspectives using depth information is also incorporated by reference herein in its entirety. In many embodiments of the invention, the process of estimating depth and/or synthesizing a higher resolution image of a scene from a set of images involves selection of a reference viewpoint, typically that of a reference camera.

In many embodiments, a set of images is created using the image data captured by the cameras in the array camera module and can be considered to be a number of images of the scene captured from different viewpoints. In order to assist with depth estimation and/or synthesis of higher resolution images, the set of images can be normalized to

increase the similarity of corresponding pixels within the images. In several embodiments, the process of estimating depth and/or building a depth map of the scene from the reference viewpoint involves determining depth estimates for pixel locations in an image from the reference viewpoint using at least a subset of the set of images, wherein generating a depth estimate for a given pixel location in the image from the reference viewpoint includes: identifying pixels in the at least a subset of the set of images that correspond to the given pixel location in the image from the reference viewpoint based upon expected disparity at a plurality of depths; comparing the similarity of the corresponding pixels identified at each of the plurality of depths; and selecting the depth from the plurality of depths at which the identified corresponding pixels have the highest degree of similarity as a depth estimate for the given pixel location in the image from the reference viewpoint. When the array camera module captures image data in multiple color channels, the array camera can compare the similarity of pixels that are identified as corresponding at each of the plurality of depths by comparing the similarity of the pixels that are identified as corresponding in each of the color channels at each of the plurality of depths. These processes are discussed in more detail in U.S. Pat. No. 8,619,082, the relevant disclosure of which is incorporated by reference herein and above by reference in its entirety.

In a number of embodiments, a higher resolution image is synthesized from the set of images obtained from the array camera module by fusing pixels from the set of images using the depth estimates to create a fused image having a resolution that is greater than the resolutions of the images in the set of images. The fusion process can include: identifying the pixels from the set of images that are visible in an image from the reference viewpoint using the at least one visibility map; applying scene dependent geometric shifts to the pixels from the set of images that are visible in an image from the reference viewpoint to shift the pixels into the reference viewpoint, where the scene dependent geometric shifts are determined using the current depth estimates; and fusing the shifted pixels from the set of images to create a fused image from the reference viewpoint having a resolution that is greater than the resolutions of the images in the set of images. In several embodiments, the process of synthesizing a higher resolution image involves performing an additional super-resolution process based upon the fused image from the reference viewpoint, the set of images captured from different viewpoints, the current depth estimates, and the visibility information. The fusion and super-resolution processes are described in more detail in U.S. Patent Publication No. 2012/0147205 the relevant disclosure of which is incorporated by reference herein and above in its entirety.

In many embodiments, the processor 108 is able to synthesize an image from a virtual viewpoint. In a number of embodiments, a virtual viewpoint is any viewpoint which is not the reference viewpoint. In several embodiments, the virtual viewpoint corresponds to a viewpoint of one of the cameras 104 in the array camera module 102 that is not the reference camera. In many embodiments, the processor is able to synthesize an image from a virtual viewpoint, which does not correspond to any camera 104 in the array camera module 102.

Although specific array camera architectures are described above with respect to FIG. 1, alternative architectures can also be utilized in accordance with embodiments of the invention. Array camera modules including independently aligned lens stacks in accordance with embodiments of the invention and discussed further below.

Array Camera Modules

Array camera modules incorporating independently aligned lens stacks can offer a variety of benefits including (but not limited to) capturing image data using focal planes that are located at the back focal length of their corresponding lens stacks. In addition, array camera modules constructed in accordance with many embodiments of the invention interpose materials between sensors and lens barrels containing the lens stacks that reduce the impact of CTE mismatch between the low CTE semiconductor materials from which the sensors are fabricated and the higher CTE materials from which the lens barrels are constructed. Accordingly, array camera modules can be constructed that achieve precise alignment of optics and robustness to variations in thermal conditions.

An array camera module incorporating independently aligned lens stacks in accordance with an embodiment of the invention is illustrated in FIGS. 2A-2C. FIGS. 2B and 2C illustrate cross sections of an array camera module 102 illustrated in FIG. 2A taken along an axis 164. The array camera module 102 includes a carrier 300, which can be implemented using a ceramic carrier and/or any of a variety of materials possessing rigidity and low CTE that are appropriate to the requirements of a specific application. Windows extend from a first side 302 through to a second side 204 of the carrier 300. Windows can be holes and or transparent regions of the carrier. In the illustrated embodiment, the windows are rectangular holes and color filters and/or IR cut-off filters 305 are mounted within the opening of each hole. As discussed above, the inclusion of spectral filters in openings within the carrier is optional and spectral filters can be located within the lens barrels and/or on the sensor elements of the focal planes. At least one sensor 310 is mounted on the first side 302 of the carrier so that the sensor pixels are positioned facing inward to receive light that passes through the color filter 305 mounted within the carrier 300. In the illustrated embodiment, a single sensor is shown per camera. As noted above, a single sensor can form the focal planes of multiple cameras. In many embodiments, a single sensor forms the focal planes of all of the cameras in the array. In several embodiments, the single sensor includes a single array of pixels that is read out to capture an image from each of the optical channels formed by the lens barrels. In many embodiments, the single sensor includes a separate independently controllable array of pixels that form the focal planes of each of the cameras. A lens barrel 320 containing a lens stack is mounted on the second side 304 of the carrier 300. The lens barrel forms an aperture and each lens barrel 320 is positioned so that the outermost lens 322 of the lens stack contained within the lens barrel directs light into the lens stack. In many embodiments, cameras in the array camera module image different parts of the electromagnetic spectrum and the lens stacks contained within the lens barrels differ depending upon the color channel to which the camera belongs. In several embodiments, the surfaces of the lens elements, and/or the material used in the construction of the lens elements within the lens stacks differ based upon the portion of the spectrum imaged by a camera. A module cap 330 is fixed to the carrier 300 and extends over the lens barrels 320. In the illustrated embodiment, the outermost lens 322 contained within each lens barrel 320 receives light through an opening in the module cap 330. The openings in the module cap 330 can be dimensioned to avoid the module cap 330 from obscuring the fields of view of the lens stacks and/or reflecting light into the lens stacks.

In other embodiments, the module cap can include one or more cover glasses through which the lens barrels can receive light.

Although the array camera modules discussed above with respect to FIGS. 2A-2C utilize a separate sensor mounted to the carrier for each camera in the array camera module, a single sensor or multiple sensors incorporating more than one focal plane can be mounted to one side of carrier with a separate lens barrel for each camera mounted to the other side of the carrier. The sensor(s) need not be mounted to the same carrier as the lens barrels. The substrate to which the sensor(s) are mounted, whether the carrier or a separate substrate, can include circuit traces that provide power to the sensor(s) and enable read out of data. Furthermore, the sensor(s) can be mounted to a substrate and independent carriers can be utilized to mount the lens barrels to the sensor(s). In embodiments that utilize multiple sensors, the sensors can communicate with another device mounted to the substrate that multiplexes data received from the sensors and provides an interface via which a processor can read out multiplexed data and control the imaging parameters of the focal planes within the array camera module. Processes for constructing array camera modules in accordance with embodiments of the invention are discussed further below.

Manufacturing Array Camera Modules

A variety of processes can be utilized to construct array camera modules in accordance with embodiments of the invention and the specific processes that are utilized typically depend upon the materials utilized in the construction of the array camera module and the manner in which one or more sensors and/or each camera's lens barrel is mounted. In a number of embodiments, the process of manufacturing an array camera module includes independently actively aligning each lens barrel.

A process for manufacturing an array camera module utilizing a carrier to which one or more sensors and camera lens barrels are independently mounted using active alignment in accordance with an embodiment of the invention is illustrated in FIGS. 3-13. The process 350 includes manufacturing (360) a carrier. As noted above with respect to FIGS. 2A-2C, in many embodiments each camera is formed around a window in the carrier that enables a lens stack contained within a lens barrel to direct light onto the focal plane of a sensor. Furthermore, a color filter and/or an IR cut-off filter can be mounted within an opening in the carrier that forms window. Accordingly, the process of manufacturing the carrier includes forming the appropriate windows, which can involve forming holes through the carrier or applying light blocking masks to a transparent carrier to define transparent windows through the carrier. In several embodiments, ledges are formed within the holes to facilitate the mounting of color filters and/or IR cut-off filters within the hole.

Referring again to FIG. 3 and FIGS. 4 and 5, color filters and/or additional filters such as (but not limited to) IR cut-off filters can be mounted (362) so that light passes through the filters in order to pass from one side of the carrier through a window to the other side of the carrier. In the embodiment illustrated in FIGS. 4 and 5, green 306, blue 307, and red 308 color filters are inserted along with IR cut-off filters into holes 301 formed within the carrier 300. The carrier is configured to be incorporated into an array camera module containing nine cameras and green color filters are incorporated within five of the cameras, two cameras incorporate blue color filters 307 and two cameras incorporate red color filters 308. The configuration of the cameras forms the π filter group conceptually illustrated in FIG. 6 in which red

and blue cameras are located equidistant and on either side of a central green camera that can serve as a reference camera. In other embodiments, any of a variety of filters applied in any of a variety of patterns can be utilized as appropriate to the requirements of specific applications. Furthermore, many applications do not involve the application of filters to the carrier. For example, an array camera module that includes one or more Bayer cameras can utilize one or more sensors to which color filters are directly applied. In many embodiments, the techniques described above are utilized to form a π filter group with a central Bayer camera or an array in which each camera is a Bayer camera. The specific selection of filters typically depends upon the requirements of a specific application.

Referring again to FIG. 3, one or more sensors are mounted (364) to the carrier so that light passing through the windows in the carrier is incident on the focal planes of the sensor(s). The mounting of sensors that each contain a single focal plane is illustrated in FIGS. 7 and 8. Each sensor 310 is mounted to a first side 302 of the carrier 300. In many embodiments, the color filters are mounted within or covering the opening on the second side 304 of the carrier. In many embodiments, flip chip mounting is utilized to mount the one or more sensors to the carrier. As can readily be appreciated, the mounting of one or more sensors to the carrier is optional. Sensors can be mounted to another substrate that is fixed in a location relative to a carrier to which the lens barrels of the cameras are mounted at some stage during the construction of the array camera module.

Referring again to FIG. 3, the process 350 includes independently mounting (366) each of the lens barrels of the cameras to the carrier. The mounting of lens barrels 320 to the second surface 304 of the carrier 300 is conceptually illustrated in FIGS. 9 and 10. In many embodiments, active alignment is utilized to align each of the lens barrels to the carrier. In order to facilitate active alignment, the windows in the carrier which define the mounting locations of the lens barrels and the dimensions of the lens barrels are determined to enable an active alignment tool to grip the lens barrel during active alignment.

In several embodiments, lens barrels can be placed close together by utilizing the ability of an active alignment tool to grip a lens barrel located adjacent three other lens barrels in a 2×2 array at an angle relative to the rows and columns of the 2×2 array. In this way, the gripper of the active alignment tool does not need to extend through the narrowest portion of the gap between any two of the adjacent lens barrels in order to place a lens barrel. Therefore, the gap between any two adjacent lens barrels is not dependent upon the dimensions of the gripper of the active alignment tool. An active alignment tool gripping a lens barrel at a 45 degree angle relative to a 2×2 array formed by the gripped lens barrel and three adjacent lens barrels in accordance with an embodiment of the invention is illustrated in FIG. 11. As can readily be appreciated the width of each member 370 of the gripper is greater than the spacing between adjacent lens barrels. By clasping the members of the gripper so that they contact lens barrel 9 at an angle relative to the rows and columns of the array of lens barrels, the members 370 of the gripper need not extend into the narrowest portion of the gap between adjacent lens barrels (2) and (5). While the axis on which the lens barrel is gripped in the illustrated embodiment is at a 45 degree angle relative to the axes of the rows and columns of the lens barrel array, the specific angle of the axis on which the lens barrel is gripped relative to the axes of the rows and columns of the lens barrel array is largely determined based upon the dimensions of the gripper of the

active alignment machine and the available spacing between adjacent lens barrels. In the illustrated embodiment, the lens barrels **320** are numbered to indicate the order in which the lens barrels were placed on the carrier **300**. The first lens barrel (1) placed on the carrier using the active alignment machine was placed in the center of the carrier. Lens barrels (2), (3), (4), and (5) were then placed in the remaining positions within a 3×3 array that are not corners. Finally, lens barrels (6), (7), (8), and (9) were placed in the corners of the 3×3 array.

Although a specific sequence is illustrated in FIG. **11**, alternative sequences can be utilized in which a pair of lens barrels is identified (4) and (7) and a third lens barrel (10) is placed using active alignment to form an L shape. A 2×2 array of lens barrels (4), (7), (10), and (11) can then be formed by positioning the gripper to contact the lens barrel of a fourth lens barrel (11) along an axis at an angle relative to the axis of the rows and columns of the 2×2 array. The process can then be repeated with respect to each adjacent pair of lens barrels (e.g. lens barrels 7 and 3) and/or each L shaped group of lens barrels formed by the placement of lens barrels (e.g. lens barrels 4, 6, and 10). Provided that the active alignment tool is not required to attempt to place a lens barrel between two lens barrels to form three lens barrels aligned along an axis, the spacing between the lens barrels can be determined in a manner that is not related to the dimensions of the gripper used to clasp the lens barrel during the active alignment process.

While specific processes for independently aligning lens stacks within an array camera module are described above with respect to FIGS. **9-11**, any of a variety of techniques including passive and/or active alignment processes can be utilized as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

Referring back to FIG. **3**, a module cap can be mounted (**368**) over the lens barrels and attached to the carrier to protect the lens barrels. Attachment of a module cap to a carrier in accordance with an embodiment of the invention is illustrated in FIG. **12**. As noted above, the module cap **330** includes openings **332** that admit light into the lens stacks contained within the lens barrels **320**. Ideally, the openings in the module cap are dimensioned so that the module cap is not visible within the field of view of any of the lens stacks and/or so that light does not reflect from the module cap into the lens stacks. In several embodiments, a small air gap exists between the module cap and the top of the lens barrels. A small bead of adhesive can be applied to each of the lens barrels to seal the air gap between the module cap and the lens barrels. In a number of embodiments, the module cap is constructed from a low CTE polymer such as (but not limited to) a glass filled liquid crystal polymer. By utilizing a low CTE polymer, warping of the lens barrels due to CTE mismatch between the carrier and the module cap can be avoided. In other embodiments, the module cap can be constructed from any material appropriate to the requirements of a specific application.

Although a variety of processes are described above in reference to FIGS. **3-12** with respect to the manufacture of array camera modules, various aspects of the processes described above can be utilized to construct any of a variety of array camera modules that incorporate an array of independently aligned lens stacks as appropriate to the requirements of specific applications in accordance with embodiments of the invention. Furthermore, not all of the components discussed above need to be mounted to the same carrier and/or additional components can be mounted to carriers in accordance with embodiments of the invention.

Array camera modules that incorporate an interface device mounted within the array camera module to enable communication with a processor in accordance with embodiments of the invention are discussed further below.

Interfacing with External Devices

Reading image data from an array camera module can involve reading image data from each of the active sensors within the array camera module. The process of communicating with each of the sensors in an array camera module can be simplified by utilizing a separate interface device that is responsible for multiplexing image data received from multiple sensors for output to an external device and for controlling imaging parameters of individual sensors in response to commands received from external devices. In a number of embodiments, the substrate or carrier to which the sensors are mounted includes electrical traces that can be utilized to carry signals between the sensors and the interface device.

An array camera module including a carrier on which a 3×3 array of sensors and an interface device are mounted is illustrated in FIG. **13**. The 3×3 array of sensors **310** and the interface device **400** are mounted to a carrier **300** on which circuit traces **402** are patterned. In a number of embodiments, the sensors **310** communicate with the interface device **400** using low-voltage differential signaling (LVDS). In several embodiments, a common clock signal coordinates the capture and readout of image data by the sensors and the interface device **400** multiplexes the captured image data received via the LVDS connections for output via an interface appropriate to a specific processor. In certain embodiments, the interface device **400** communicates with external devices such as processors and/or graphics processors using a MIPI CSI 2 output interface supporting four lane video read-out of video at 30 fps from the array camera module. The bandwidth of each lane can be optimized for the total number of pixels in the sensor(s) within the array camera module and the desired frame rate. The use of various interfaces including the MIPI CSI 2 interface to transmit image data captured by an array of focal planes to an external device in accordance with embodiments of the invention is described in U.S. Pat. No. 8,305,456 to McMahon, the disclosure of which is incorporated by reference herein in its entirety. In other embodiments, any interface appropriate to the requirements of specific applications can be utilized including interfaces that enable the control of the imaging parameters of groups of focal planes by an external device in a manner similar to that described in U.S. Provisional Patent Publication No. 2014/0132810 entitled "Systems and Methods for Array Camera Focal Plane Control" to McMahon, filed Nov. 13, 2013, the disclosure of which is incorporated by reference herein in its entirety.

In embodiments where one or more sensors are mounted to a separate substrate to the carrier, an interface device can also be mounted to the substrate. A substrate assembly that can be utilized in the construction of an array camera module in accordance with an embodiment of the invention is illustrated in FIG. **14**. The substrate assembly comprises a substrate **410** to which multiple sensors **310** and an interface device **400** are attached. The substrate **410** is bonded to a carrier **300** to which lens barrels can be independently mounted utilizing processes similar to those outlined above. In many instances the substrate is bonded to the carrier and the windows through the carrier are dimensioned to provide sufficient tolerances to ensure that the focal planes of each of the sensors are positioned within the openings. Although the illustrated embodiment includes multiple sensors, a similar configuration can also be utilized with a single

sensor that forms multiple focal planes (the imaging parameters and read-out of which may or may not be independently controlled).

In many embodiments, a single sensor is utilized. A camera module in which lens barrels and a sensor are mounted to a carrier in accordance with an embodiment of the invention is illustrated in FIG. **15**. The camera module **1500** includes four lens barrels **1502** and a single sensor **1504** that are attached to a carrier **1506**, which is constructed from a transparent glass material. As can readily be appreciated, a camera module to which lens barrels and a single sensor are attached can utilize any of a variety of carrier materials as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

Although the present invention has been described in certain specific aspects, many additional modifications and variations would be apparent to those skilled in the art. It is therefore to be understood that the present invention can be practiced otherwise than specifically described. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

What is claimed is:

1. An array camera, comprising: a processor; memory containing an image capture application; an array camera module, comprising: at least one carrier in which at least one window is formed; at least one sensor mounted relative to the at least one carrier so that light passing through the at least one window in the at least one carrier is incident on a plurality of focal planes formed by at least one array of pixels on the at least one sensor; a plurality of lens barrels mounted to the at least one carrier, so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels; wherein the image capture application directs the processor to: trigger the capture of image data by the array camera module; obtain and store image data captured by the array camera module, where the image data forms a set of images captured from different viewpoints; select a reference viewpoint relative to the viewpoints of the set of images captured from different viewpoints; normalize the set of images to increase a similarity of corresponding pixels within the set of images; determine depth estimates for pixel locations in an image from the reference viewpoint using at least a subset of the set of images, wherein generating a depth estimate for a given pixel location in the image from the reference viewpoint comprises: identifying pixels in the at least a subset of the set of images that correspond to the given pixel location in the image from the reference viewpoint based upon expected disparity at a plurality of depths; comparing the similarity of the corresponding pixels identified at each of the plurality of depths; and selecting the depth from the plurality of depths at which the identified corresponding pixels have the highest degree of similarity as a depth estimate for the given pixel location in the image from the reference viewpoint.

2. The array camera of claim **1**, wherein the at least one carrier is a single carrier.

3. The array camera of claim **2**, wherein:
each of the plurality of sensors is mounted to a first side of the single carrier;
each of the plurality of lens barrels is mounted to a second opposite side of the single carrier; and

the plurality of sensors comprises a separate sensor for each of the plurality of lens barrels.

4. The array camera of claim **2**, wherein:
the plurality of sensors is mounted to a substrate and the single carrier is mounted in a fixed location relative to the substrate; and
the plurality of sensors is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

5. The array camera of claim **2**, wherein the at least one sensor is a single sensor.

6. The array camera of claim **5**, wherein:
the single sensor is mounted to a first side of the single carrier; and
each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

7. The array camera of claim **5**, wherein:
the single sensor is mounted to a substrate and the single carrier is mounted in a fixed location relative to the substrate; and
the single sensor is positioned proximate a first side of the single carrier and each of the plurality of lens barrels is mounted to a second opposite side of the single carrier.

8. The array camera of claim **1**, wherein:
the at least one sensor is mounted to a substrate and each of a plurality of carriers is mounted in a fixed location relative to the substrate; and
each of the plurality of lens barrels is mounted to a separate carrier.

9. The array camera of claim **1**, wherein:
each lens barrel and corresponding focal plane forms a camera;
different cameras within the array camera module image different parts of the electromagnetic spectrum; and
the lens stacks contained within the lens barrels differ depending upon the portion of the electromagnetic spectrum imaged by the camera to which the lens barrel belongs.

10. The array camera of claim **1**, wherein each lens stack in the lens barrels has a field of view that focuses light so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene.

11. The array camera of claim **10**, wherein:
the pixel arrays of the focal planes define spatial resolutions for each pixel array;
the lens stacks focus light onto the focal planes so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene with sub-pixel offsets that provide sampling diversity; and
the lens stacks have modulation transfer functions that enable contrast to be resolved at a spatial frequency corresponding to a higher resolution than the spatial resolutions of the pixel arrays.

12. The array camera of claim **11**, wherein the image capture application further directs the processor to fuse pixels from the set of images using the depth estimates to create a fused image having a resolution that is greater than the resolutions of the images in the set of images by:
determining the visibility of the pixels in the set of images from the reference viewpoint by:
identifying corresponding pixels in the set of images using the depth estimates; and
determining that a pixel in a given image is not visible in the reference viewpoint when the pixel fails a photometric similarity criterion determined based upon a comparison of corresponding pixels; and

applying scene dependent geometric shifts to the pixels from the set of images that are visible in an image from the reference viewpoint to shift the pixels into the reference viewpoint, where the scene dependent geometric shifts are determined using the current depth estimates; and

fusing the shifted pixels from the set of images to create a fused image from the reference viewpoint having a resolution that is greater than the resolutions of the images in the set of images.

13. The array camera of claim 12, wherein the image capture application further directs the processor to synthesize an image from the reference viewpoint by performing a super-resolution process based upon the fused image from the reference viewpoint, the set of images captured from different viewpoints, the current depth estimates, and visibility information.

14. The array camera of claim 1, wherein at least one spectral filter is mounted within at least one window in the at least one carrier.

15. The array camera of claim 14, wherein the at least one spectral filter is selected from the group consisting of a color filter and an IR-cut filter.

16. The array camera of claim 1, wherein at least one spectral filter is applied to an array of pixels forming a focal plane on at least one of the sensors.

17. The array camera of claim 1, wherein at least one lens stack includes at least one spectral filter.

18. The array camera of claim 1, wherein:

the plurality of images comprises image data in multiple color channels; and

the image capture application directs the processor to compare the similarity of pixels that are identified as corresponding at each of the plurality of depths by comparing the similarity of the pixels that are identified as corresponding in each of a plurality of color channels at each of the plurality of depths.

19. The array camera of claim 1, wherein the plurality of lens barrels and the plurality of focal planes form an M×N array of cameras.

20. The array camera of claim 19, wherein the plurality of lens barrels and the plurality of focal planes form a 3×3 array of cameras.

21. The array camera of claim 19, wherein the M×N array of cameras comprises a 3×3 group of cameras comprising:

a central reference camera;

four cameras that capture image data in a first color channel located in the four corners of the 3×3 group of cameras;

a pair of cameras that capture image data in a second color channel located on either side of the central reference camera; and

a pair of cameras that capture image data in a third color channel located on either side of the central reference camera.

22. The array camera of claim 21, wherein the reference camera is selected from the group consisting of: a camera including a Bayer filter; and a camera that captures image data in the first color channel.

23. The array camera of claim 1, wherein the array camera module further comprises an interface device in communication with the at least one sensor, where the interface device multiplexes data received from the sensors and provides an interface via which the processor reads multiplexed data and via which the processor controls the imaging parameters of the focal planes formed by the plurality of pixel arrays.

24. The array camera of claim 23, wherein:

the interface device is mounted to the carrier and the carrier includes circuit traces that carry signals between the interface device and the at least one sensor; and

a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

25. The array camera of claim 23, wherein:

the at least one sensor and the interface device are mounted to a substrate, which includes circuit traces that carry signals between the interface device and the at least one sensor;

the at least one carrier is mounted in a fixed location relative to the at least one sensor; and

a common clock signal coordinates the capture of image data by the at least one sensor and readout of the image data from the at least one sensor via the interface device.

26. The array camera of claim 1, wherein the module cap is mounted to the at least one carrier so that a small air gap exists between the module cap and the top of the lens barrels and a small bead of adhesive seals the air gaps between the module cap and the lens barrels.

27. The array camera of claim 1, wherein the carrier is constructed from a material selected from the group consisting of ceramic and glass.

28. A array camera, comprising: a processor; memory containing an image capture application; an array camera module, comprising: a carrier in which a plurality of windows are formed; a plurality of sensors each including an array of pixels, where the plurality of sensors are mounted relative to the carrier so that light passing through the plurality of windows is incident on a plurality of focal planes formed by the arrays of pixels; a plurality of lens barrels mounted to the at least one carrier so that a lens stack in each lens barrel directs light through the at least one window in the at least one carrier and focuses the light onto one of the plurality of focal planes; and a module cap mounted over the lens barrels, where the module cap includes at least one opening that admits light into the lens stacks contained within the plurality of lens barrels; wherein the image capture application directs the processor to: trigger the capture of image data by the array camera module; obtain and store image data captured by the array camera module, where the image data forms a set of images captured from different viewpoints; select a reference viewpoint relative to the viewpoints of the set of images captured from different viewpoints; normalize the set of images to increase a similarity of corresponding pixels within the set of images; determine depth estimates for pixel locations in an image from the reference viewpoint using at least a subset of the set of images, wherein generating a depth estimate for a given pixel location in the image from the reference viewpoint comprises: identifying pixels in the at least a subset of the set of images that correspond to the given pixel location in the image from the reference viewpoint based upon expected disparity at a plurality of depths; comparing the similarity of the corresponding pixels identified at each of the plurality of depths; and selecting the depth from the plurality of depths at which the identified corresponding pixels have the highest degree of similarity as a depth estimate for the given pixel location in the image from the reference viewpoint.

29. The array camera of claim 28, wherein:

the pixel arrays of the focal planes define spatial resolutions for each pixel array;

the lens stacks focus light onto the focal planes so that the plurality of arrays of pixels that form the focal planes sample the same object space within a scene with sub-pixel offsets that provide sampling diversity; and

the lens stacks have modulation transfer functions that enable contrast to be resolved at a spatial frequency corresponding to a higher resolution than the spatial resolutions of the pixel arrays; and

the image capture application further directs the processor to fuse pixels from the set of images using the depth estimates to create a fused image having a resolution that is greater than the resolutions of the images in the set of images by:

determining the visibility of the pixels in the set of images from the reference viewpoint by:

identifying corresponding pixels in the set of images using the depth estimates; and

determining that a pixel in a given image is not visible in the reference viewpoint when the pixel fails a photometric similarity criterion determined based upon a comparison of corresponding pixels; and

applying scene dependent geometric shifts to the pixels from the set of images that are visible in an image from the reference viewpoint to shift the pixels into the reference viewpoint, where the scene dependent geometric shifts are determined using the current depth estimates; and

fusing the shifted pixels from the set of images to create a fused image from the reference viewpoint having a resolution that is greater than the resolutions of the images in the set of images.

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